INFLUENCE OF SMALL VESSEL OPERATION AND PROPULSION SYSTEM ON LOGGERHEAD SEA TURTLE INJURIES

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INFLUENCE OF SMALL VESSEL OPERATION AND PROPULSION SYSTEM ON LOGGERHEAD SEA TURTLE INJURIES

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[To Claudia, who inspired me to begin this work.]

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SUMMARY

Loggerhead sea turtles (*Caretta caretta*) can be found worldwide, inhabiting tropical and subtropical coastal waters. The loggerhead was classified as an endangered species and placed on the International Union for Conservation of Nature and Natural Resources (IUCN) Red List in 1996 (IUCN 2006).The problem of sea turtle mortality as a result of collisions with vessels is of increasing concern, especially in the southeastern United States, where increased development along the coasts results in increased recreational boat traffic. In the United States, the percentage of strandings that were attributed to vessel strikes has increased from approximately 10% in the 1980's to a record high of 20.5% in 2004 (NMFS 2007).

This report presents results from field experiments designed to investigate the ways in which loggerhead sea turtles are injured in boat collisions, and the effectiveness of several mitigation options for reducing the risk of fatal interactions. In order to conduct these field experiments, a synthetic sea turtle carapace was designed and built that approximated the structural behavior of a biological sea turtle carapace. Hodges (2008) quantified the material strength properties of loggerhead sea turtle carapaces. From these results, it was determined that the target parameter for simulating tensile strength in a synthetic carapace should be force per unit width of sample. Hodges designed and constructed an artificial carapace made of composite material for use in controlled experiments.

Modifications were made to the design proposed by Hodges (2008) to facilitate rapid construction. Several designs were tested using the force per unit width as the

target strength parameter and compared to the strength of the biological carapace. Tests on the design ultimately adopted showed a force per unit width 17.6% stronger than the biological carapace. The composite material being stronger than the biological carapace means the testing will result in conservative reports of damage. Once the design and construction methods were finalized, approximately 60 artificial carapaces were fabricated for field testing. A frame, weighting scheme and buoyancy unit were designed and fabricated so that each test carapace floated at proper draft and had realistic specific gravity and weight.

Field testing procedures were designed to investigate the influence of a) boat speed, b) animal position in the water column, and c) vessel propulsion system on the severity of vessel collisions on turtles. All experiments were done with small (<6 m in length) vessels. Boat/sea turtle collisions were simulated by placing a test specimen (a synthetic carapace attached to a test frame) in the water column and striking it with the vessel. The speeds considered were idle (7 km/h), sub-planing (14 km/h), and planing (40 km/hr). The two animal positions in the water column were 1) at the water surface and 2) at "prop depth" (depth to the center of the propeller hub on the standard outboard motor). Five propulsion options were tested: 1) a standard outboard motor, 2) a standard outboard motor with Hydroshield® propeller guard 3) a standard outboard motor with Prop Buddy® propeller guard, 4) a jet outboard motor and 5) a jet-propelled personal watercraft, often referred to generically as a "jet ski". The experiments typically included five trials per test configuration.

Catastrophic (presumably fatal) damage was defined to occur when any damage penetrated the carapace. Small wounds (< 4 cm in length) along the sides or rear of the artificial carapace, where the shell and bone extend beyond the edge of the body cavity, were not classified as catastrophic This definition was used to classify the effectiveness of the various mitigation options.

Results indicate that reducing the speed of the vessel reduces the odds of severe damage to the animals. Of all of the tests performed with the standard outboard motor (including tests with propeller guards installed), 25% of those performed at idle speed resulted in catastrophic damage, compared to 100% for planing speed tests. The two tested propeller guards both modified the type of damage to the animal when compared to similar tests with the standard motor configuration, but they only slightly reduced the risk of catastrophic damage. At idle speed, with propeller guard installed, 10% of the tests resulted in catastrophic damage. The corresponding number for the standard motor was 40%. At planing speed, 100% of the tests resulted in catastrophic damage, with or without the propeller guard.

No catastrophic injuries were observed during testing of both jet propulsion systems (jet outboard and jet ski) at any speed or depth in the water column. Both feature a much smaller draft than the standard outboard, which results in little chance of striking an animal below the surface. And both the jet outboard and the jet-powered watercraft feature water intakes that are relatively smooth and appeared to slide across the animal with minimal damage to the carapace when the model animal was floating on the surface.

The experiments described here involved a limited range of hull configurations; results may be different for hulls or propulsion systems drastically different than those tested here. But the results obtained indicate that equipment, in the form of the boat's propulsion system, and the mode in which it is used both play a role in defining the risk of boats to turtles in the field.

CHAPTER 1

INTRODUCTION

Loggerhead sea turtles (*Caretta caretta*) can be found worldwide, inhabiting tropical and subtropical coastal waters. They have been observed in the western Atlantic from Newfoundland to Argentina (Plotkin 1995). In the United States, their primary nesting habitat includes beaches from North Carolina through Florida. The loggerhead forages in nearshore, estuarine environments and reproduces by laying eggs on beaches (Ernst et al. 1994). Adults have an average carapace length of 92 cm and an average mass of 115 kg (Plotkin 1995). Age to maturity is influenced by many factors such as food quality and quantity and average water temperature. Depending on these factors, female loggerhead turtles may reach maturity between 10 and 30 years, with as many as 32 years of reproductive activity afterwards (Plotkin 1995).

Anthropogenic effects on sea turtle population and mortality are well documented in the literature. The loggerhead was classified as an endangered species and placed on the International Union for Conservation of Nature and Natural Resources (IUCN) Red List in 1996 (IUCN 2006). The recovery plan for the northwest Atlantic population of the loggerhead sea turtle (Caretta caretta) lists the major threats to sea turtles in the U.S. as destruction or alteration of nesting habitats, incidental capture in commercial or recreational fishing gear, entanglement in marine debris, and vessel strikes (NMFS 2008). Regulations have been enacted to attempt to reduce the number of turtles killed as incidental bycatch in fisheries, and through entanglement in marine debris. Turtle Excluder Devices (TEDs) are required in all shrimping trawls and numerous studies have been done to determine the effect of different hook types, baits, and fishing locations on sea turtle bycatch (Gilman et al. 2007, Zydelis et al. 2008).

While vessel strikes are a known cause of sea turtle mortality (Magnuson et al. 1990), there have been few studies that focus solely on the interaction between sea turtles and marine vessels. Venizelos (1993) and Hazel (2006) studied the effect of recreational vessels on the mortality rates of sea turtles in the Mediterranean and off the coast of Australia, respectively. Thomas et al. (2008) found that 23% of the sea turtle strandings on the Mediterranean coast of Spain were caused by interactions with humans, with 9% of the strandings a result of vessel strikes.

The problem of vessel strikes on sea turtles is of increasing concern, especially in the southeastern United States, where increased development along the coasts results in increased recreational boat traffic. In the United States, the percentage of strandings that were attributed to vessel strikes has increased from approximately 10% in the 1980's to a record high of 20.5% in 2004 (NMFS 2007). Many vessel strikes have been documented in southeast Florida with as many as 60% of stranded loggerheads displaying signs of propeller-related injuries (NMFS 2007). Furthermore, 15% of sea turtle fatalities in Georgia have been attributed to impacts of boats and boat propellers (M. Dodd, pers. comm.).

The work that led to this report was completed in four main phases:

1) Determination of material properties of natural loggerhead sea turtle carapace material. This was done with material harvested from animals that had been stranded on Georgia beaches either dead or with injuries that required euthanization. A new testing procedure was designed for this phase.

2) Design of a composite material with pertinent material properties similar to a natural loggerhead carapace.
3) Fabrication of a large number (~60) of artificial carapaces for field testing. Design and fabrication of a frame, weighting scheme and buoyancy unit so that the test specimen floats at proper draft and has a realistic specific gravity and weight.
4) Performance of a series of field tests to investigate the influence of vessel speed, propulsion system (including propeller guards and jet drives) and depth in the water column on turtle injuries in boat strikes.

Phases 1) and 2) above were described in detail by Hodges (2008). Phases 3) and 4) will be the primary focus of this thesis and are described in detail in the pages that follow. It is hypothesized that increasing the speed of the vessel will increase the severity and likelihood of fatal injuries resulting from sea turtle collisions with vessels. Additionally, the severity and likelihood of fatal injury will be influenced by the configuration and type of propulsion system used in each test. Animal position in the water column is hypothesized to have little influence on the severity or likelihood of fatal injury, assuming that the animal is impacted by the vessel.

CHAPTER 2

LITERATURE REVIEW

Much work has been done examining the interaction between recreational vessels and marine mammals including manatees and whales (Curran and Morris 1988, George et al. 1994, Marmontel et al. 1997, Panigada et al. 2006, Douglas et al. 2008). Few studies have examined the interaction of recreational vessels and sea turtles. Of the work that does exist, most studies focus on the number of turtle strandings as a result of vessel strikes (Venizelos 1993, Hazel 2006, NMFS 2007). No studies investigating the influence of vessel strikes on the type and severity of injuries in sea turtles has been found in the existing literature.

A reduction in recreational vessel speed was suggested by Venizelos (1993) after a study found eight sea turtles stranded with evidence of vessel strikes in Laganas Bay, Greece in a single month. It was noted that only a fraction of sea turtles struck by vessels are actually discovered, implying that the interaction between vessels and turtles may be more detrimental to sea turtle populations than estimated. This is consistent with findings by Hart et.al. (2006) on probability of sea turtles killed offshore reaching the coast. This study used sea turtle stranding data and drift bottle data, along with results from an oceanographic model, to determine the probability that a sea turtle killed offshore would eventually reach the coast. The study concluded that approximately 20% of turtles killed would reach the coast within two weeks of death. The authors note that the probability varies with temporal changes in winds and currents as well as spatial differences (location along and distance from the coast).

After reviewing the stranding records in Queensland, Australia, Hazel (2006) expressed concern over increased boat traffic, suggesting it would have a negative impact on the effectiveness of mitigation programs intended to protect sea turtles. It was discovered that a minimum of sixty-five sea turtles were killed annually as a result of boat strikes off the coast of Australia. Adult green and loggerhead turtles made up 72% of the strandings recorded. This number is comparable to the fraction of mortalities attributed to bycatch from fishing trawls prior to Australia's mandatory introduction of Turtle Excluder Devices. In a similar study, Oros et-al. (2005) found that of the 93 sea turtles stranded along the coast of the Canary Islands, Spain over a 4-year period from 1998-2001, 23% of the stranded turtles died as a result of wounds from boat strikes.

Studies on sea turtle diving habits have shown that turtles tend to make shallower dives (< 1m depth) during the day in nearshore, foraging environments. Turtles have been recorded spending up to six hours in these shallow dives, with the peak times being around sunrise and sunset (Hazel et al. 2009). This diving behavior is also more common during warmer months, corresponding with peak times and locations for recreational vessel activity. This increased boat activity, along with the turtle's shallow position in the water column, increases the chance of interaction between turtles and vessels. Visual observations suggest that sea turtles make only brief appearances at the surface, often staying visible for less than two seconds. Even then, only the head is usually exposed. This behavior could result in an increase in vessel strikes because the turtle is not readily visible to vessel operators.

Hazel (2007) conducted a study to evaluate the behavior of sea turtles near an approaching vessel. Data was collected for vessels approaching sea turtles at various speeds in shallow water. The study indicated that as the speed of the approaching vessel increased, the response of the turtle to avoid the vessel decreased. The author concluded that vessels traveling faster than four km/hr could not rely on the turtle to actively respond to avoid a collision. Idle speed for many recreational motor vessels exceeds this four km/hr speed limit, suggesting that in the majority of vessel strikes the animal response to the approaching vessel will be essentially nonexistent.

Hodges (2008) summarized loggerhead sea turtle strandings in the state of Georgia, and classified the locations and types of vessel-related injuries. The author examined photographs of 110 sea turtles stranded in Georgia between 2001 and 2006. These photographs were examined and the location of wounds and probable cause of the damage were recorded. The location of damage was divided into four categories: front, middle and rear third of the carapace and along the rim of the carapace. Causes of the injuries were defined as propeller, skeg, blunt object, and indeterminate. Results indicated that the highest number of observed wounds occurred due to a skeg impact to the center of the carapace.

Hodges (2008) also tested natural loggerhead carapace material properties, and developed a synthetic composite to simulate the properties of a biological carapace (described in more detail in the next section). No other research directly examining the material properties of loggerhead turtle carapaces has been found. However, many studies have been conducted to quantify the material properties of other biological materials such as human and animal bones, or to investigate the properties of biological materials for inspiration in designing new construction materials. Several of these studies are reviewed below.

Recently there has been an increase in the development of synthetic materials that mimic properties of biological materials. The structural makeup of bamboo has been studied, for example, because of the high strength to weight ratio displayed by the plant. The findings showed that a double-helical structure was optimum for the development of high strength composite materials (Li et-al. 1995). Mayer (2005) investigated the high strength of mollusk shells. The molecular structure of mollusks displays a brick and mortar design. Models mimicking this structure (composed of ceramic and organic material) were subjected to mechanical testing, resulting in a greater understanding of the energy dissipation in this type of matrix.

Much of the testing of biological materials has focused on the structural properties of bone. Garita and Rapoff (2003) investigated the behavior of human bone subjected to static and cyclic loading to determine the optimum geometry that maximizes strength while minimizing weight. The findings suggested that a bone-like material with varying densities displayed twice the strength of homogeneous material subjected to identical loading. This could be beneficial in engineering structures displaying discontinuities.

Traditional methods for testing materials may not be applicable to the testing of biological samples, due to their non-homogeneity. In bone, this non-homogeneity is a result of collagen and elastic fibers, and can vary based on the age, diet, and lifestyle of the biological specimen (Karchin 2004). Biological samples often require testing in different orientations to determine elastic constants along planes of symmetry (transversely isotropic-orthotropic) (An and Draughn 1999). Tensile testing poses an additional problem, as the biological sample will often slip from the grips of the tensometer resulting in errors in computed strain and modulus values (Milthorpe et al. 1987). Hodges (2008) developed specialized tabs to solve this problem in the tensile testing of loggerhead turtle carapace samples by seating the sample coupon in epoxy contained in a PVC cap and attaching steel tabs to be gripped by the tensometer.

Currey (1984) tested the bones of several species to evaluate the effects of varying mineralization on the strength properties of bones. The author noted that most strength testing on bones is performed by applying a force to the specimen at low displacement rates. However, this may not represent the conditions of bones breaking in nature due to the rapid absorption of a large amount of kinetic energy. The author also argued that the carefully prepared samples used in strength testing may not contain the same natural imperfections that are found in animal bones, where most breaks start. The author suggested that these considerations be considered when comparing the behavior of natural bones to strength testing data.

An additional problem with strength testing of the bone material is that the samples must be cut and/or milled and shaped to form a test coupon. Any burning resulting from cutting and milling can significantly affect the structural mechanical properties (An and Draughn 1999). Burstein et al (1976) used a water jet to reduce burn damage to the sample. To mitigate the effects of burning, Hodges (2008) used a water cooled circular saw to harvest the sample coupons of the loggerhead sea turtle carapaces.

The preparation and preservation of samples can also affect the measured strength of biological materials. An and Draughn (1999) determined that unpreserved human bone samples exhibit a 3% decrease in elasticity after 24 hours. The author suggested that samples be frozen and kept hydrated for proper long-term preservation. Preservation in a solution of 50% saline and 50% alcohol is recommended for short-term preservation. Hodges (2008) preserved the sample coupons cut from the loggerhead carapaces in the saline-alcohol solution mentioned above to reduce deterioration prior to testing.

Because vessel-related injuries to manatees accounted for 24% of all manatee deaths in Florida between 1974 and 2006, Clifton et al. (2008) investigated the effect of boat strikes on manatee bones. Manatee rib bones were subjected to three point flexural tests and the strength values were determined. Manatee bones are unique because they are thicker than bones of other mammals. However it was determined that this increase in thickness did not translate to an increase in strength and this lack of strength in manatee bones made the animal more susceptible to fatal injuries from vessel strikes.

CHAPTER 3

SYNTHETIC CARAPACE DESIGN

As noted above, an earlier phase of the work described here involved a series of laboratory tests performed at Georgia Tech's Savannah campus to quantify the tensile strength of a loggerhead turtle carapace. These test results were used in the development of a synthetic carapace with matching characteristics (Hodges 2008). That original design was modified slightly to facilitate the production of test specimens to be used in field tests described here. The experimental designs were tested and compared to the strength of the biological carapace to create a design that approximates the target material properties of the biological carapace. The following sections describe the construction and testing of the artificial carapace. The original work performed to characterize the natural material is summarized in the interests of continuity and clarity.

3.1 Strength Testing of Biological Carapace

Three loggerhead carapaces were obtained from the Georgia Department of Natural Resources to determine the mechanical properties of the natural material. The loggerhead carapaces were representative of the most common size class that is found stranded on Georgia beaches with boat collision injuries (approx. 65cm curved carapace length). From these carapaces, sample coupons were harvested, both transverse and longitudinal to the spine. The tensile and flexural properties of the loggerhead carapace were determined through experimental investigation of these samples. These tests were performed using a screw-type load testing device. As there is no specified ASTM testing procedure for loggerhead carapace material, the tensile testing procedure used by Hodges (2008) was based on ASTM D 3039 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. Likewise, all flexural tests were based on ASTM D 790 – Standard Test Method for Flexural Properties of Unreinforced Plastics and Electrical Insulating Materials. The carapace material is composed of minerals and fibrous collagen, and thus bears some similarity to man-made composite materials, from a structural standpoint.

Figure 3.1. Screw type load testing device used for tensile strength testing.

The primary mechanical properties of interest available from the tensile tests were ultimate tensile strength, tensile strength at failure, and modulus of elasticity. The flexural tests provided definition of the modulus of rupture (maximum flexural stress), flexural strain at failure, and flexural modulus. Results from the tests revealed that the modulus of rupture and bending modulus from the flexural tests were significantly larger than the ultimate strength and the elastic modulus computed during tensile testing.

Because it is not possible to mimic all of the mechanical and geometrical properties of a biological carapace with synthetic composite material, Hodges (2008) analyzed the effect of the geometrical properties on the tensile strength of the biological material. This analysis indicated that the thickness of the biological sample does not have a significant influence on tensile load capacity of the sample. Therefore, it was concluded that force per unit width at failure should be the target value when simulating tensile failure of a carapace. The use of force per unit width in place of ultimate strength allowed for varying the thickness of the synthetic carapace in order to replicate the tensile force required to rupture a biological carapace. This is advantageous in the synthetic carapace design since the tensile strength per unit thickness of a typical composite material is generally much higher than that of a biological carapace. Therefore the tensile strength of the biological carapace can only be achieved with composite materials using a much thinner sample. This allows a higher strength composite material to be reduced in thickness in order to simulate the force at failure of the biological material. Table 3.1 lists the target tensile properties obtained from the biological test results.

Table 3.1. Tensile material properties of natural loggerhead turtle carapace, averaged from tests of the three biological carapaces (Hodges, 2008).

Original orientation of coupon in carapace	Ult. Tensile Strength (kPa)	Modulus (MPa)	Strain at Failure	Ult. Force / Width (N/cm)
Longitudinal	3810	328	2.60%	359
Transverse	4340	295	2.90%	457
Overall	4080	312	2.80%	408

3.2 Fabrication and Strength Testing of Original Prototype

Using the results shown in Table 3.1, Hodges (2008) constructed a synthetic carapace using a single layer of E-glass, polyester fiber-reinforced, polymeric fabric weighing 305 grams per square meter of material. The fabric was cut to the geometry of the loggerhead turtle carapace mold, and polyester resin was infused through it. Longitudinal ridges were added over the entire carapace to increase structural rigidity. The resulting force per unit width at failure of the synthetic carapace was calculated to differ from force per unit width at failure of the natural carapace by an average of +10.8%. Ultimate force per unit width within 10% deviation from the force per unit width of the biological carapace was chosen as the target value. Table 3.2 shows a comparison of these results, and Figure 3.2 shows the synthetic carapace alongside the biological carapace used as the mold.

Figure 3.2. Left: loggerhead sea turtle carapace after being filled and smoothed. Right: original prototype of synthetic carapace, with longitudinal ridges to increase stiffness against bending.

3.3 Modified Designs and Strength Testing

Production of the design proposed by Hodges (2008) proved to be too time consuming and labor intensive to allow completion of the number of synthetic carapaces needed for field testing in the available time. Some changes were incorporated to allow more rapid fabrication while still providing a close approximation of the natural material.

To fabricate the test carapaces, a mold was made from the biological carapace used by Hodges (2008) by adding a layer of fiberglass mat to the topside of the carapace. The fiberglass was trimmed to the size of the original carapace and polyester resin was applied to the mat and was allowed to harden over a period of at least 24 hours in a heated curing area. The fiberglass mold was removed from the carapace and the biological carapace was returned to the freezer. The fiberglass mold was then turned over (concave up) and its sides supported to prevent deformation from flexing during the application of expanding foam. The mold was then filled with expanding foam, until the foam expanded an inch or two above the edge of the fiberglass mold. The foam stabilized the mold and prevented it from deforming while working on it. This process was repeated until 5 molds were created so that multiple carapaces could be constructed simultaneously. Figure 3.3 shows a mold used in fabrication of synthetic carapaces.

Figure 3.3. A mold used to construct synthetic carapaces.

The first material system tested consisted of a single layer of 229 gram per square meter fiberglass mat cut to fit over the mold. The fiberglass mat was infused with polyester resin and tested for mechanical properties after curing. This design proved to be 33% weaker than the target ultimate force per unit width. Using the same procedure, another synthetic carapace consisting of a single layer of 458 gram per square meter fiberglass mat was created using the same procedure. This carapace proved to have a force per unit width 28.4% higher than the target value.

The next material design consisted of a double layer of the 229 gram per square meter fiberglass mat. One layer of the fiberglass mat was cut to fit over the mold and infused with polyester resin. Once that layer had cured, the second layer of the fiberglass cloth was positioned on top of the first and infused with resin. Testing of the mechanical properties showed this design to be 28.2 % stronger than the target material, in terms of force per unit width.

The final material design consisted of two layers of 229 gram per square meter fiberglass mat separated by a layer of 2 mm thick Coremat® (a chopped fiber polyester fabric used to add stiffness to laminates, primarily by increasing thickness, and thus area moment of inertia). The design and production details are described in detail below. This design increased the rigidity of the synthetic carapace as a whole, while bringing the force per unit width at failure closer to the target value. An internal rib structure was also added to the layer on the underside of the carapace to improve the structural rigidity of the carapace as a whole, without modifying the tensile strength significantly.

Initial tensile strength testing of this new design indicated a force per unit width at failure within +10% of that of the biological carapace, therefore this design was used in the fabrication of the synthetic carapaces used for field testing. However, additional tests resulted in an average force per unit width of 17.6% higher than that of the target value. This was most likely due to variability during the production process and the continued curing of the resin over time. These results indicate that the Coremat® spacer decreased the force per unit width compared to the double layer 229 gram fiberglass and the single layer 458 gram fiberglass. This brought the strength of the design closer to the target value while increasing the structural rigidity needed to better represent the overall physical characteristics a biological carapace. The tensile strength of each of the designs is compared to the target values in Table 3.2. A representative stress – strain curve from tensile strength tests performed on this material configuration is shown in Figure 3.4.

Table 3.2. Comparison of strength results for synthetic carapace design and biological samples.

Carapace	Ult. Force / Width (N/cm)	% Difference	Number of Samples	Standard Deviation
Biological	408		60	
Original Prototype	452	10.8	10	15.8
Single Layer 229 gram	273	33.1	5	51.8
Single Layer 458 gram	524	28.4	5	138.4
Double Layer229 gram	523	28.2	5	60.6
Two Layer of 229 gram with Coremat ® spacer	480	17.6	30	85.8

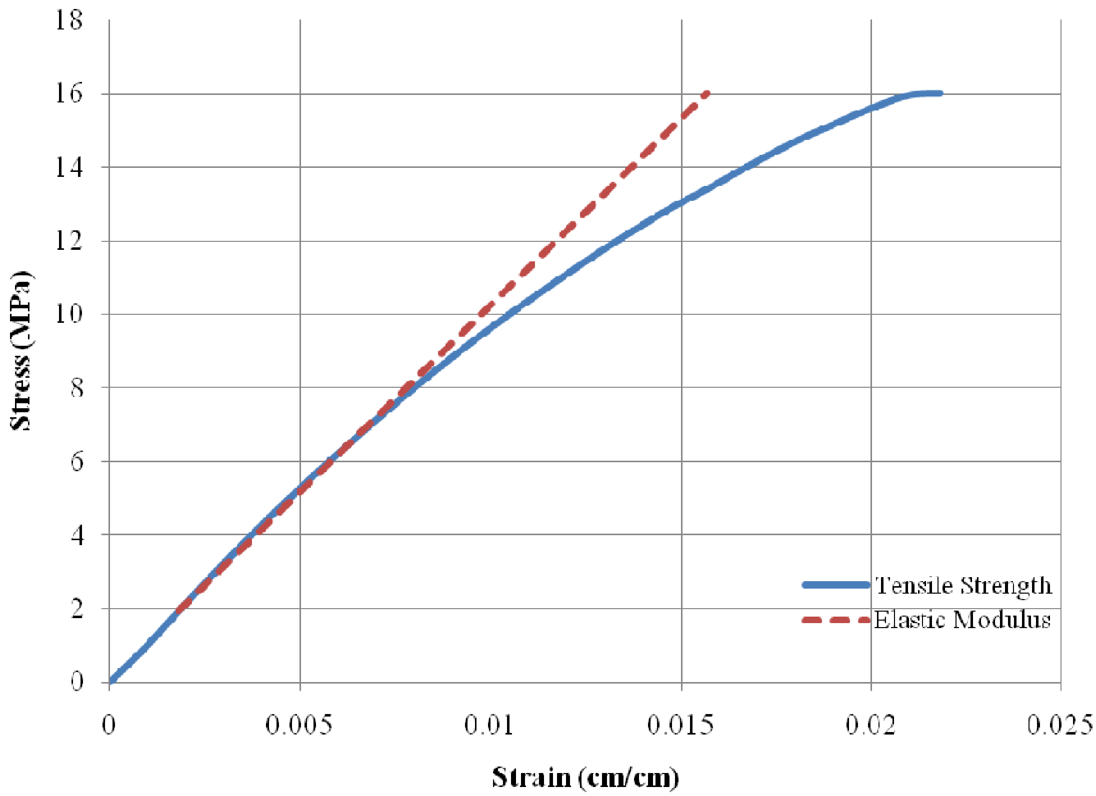


Figure 3.4. Tensile stress-strain curve for a representative sample of the double-layer 229 gram fiberglass mat with Coremat® spacer.

This final design resulted in a synthetic carapace that displayed an ultimate force per unit width close to that of the biological carapace. Figure 3.5 shows a cross-section diagram of the components of the final design. A side-by-side comparison of the original synthetic carapace designed and fabricated by Hodges (2008) and the final design of the synthetic carapace used in field testing is shown in Figure 3.6.

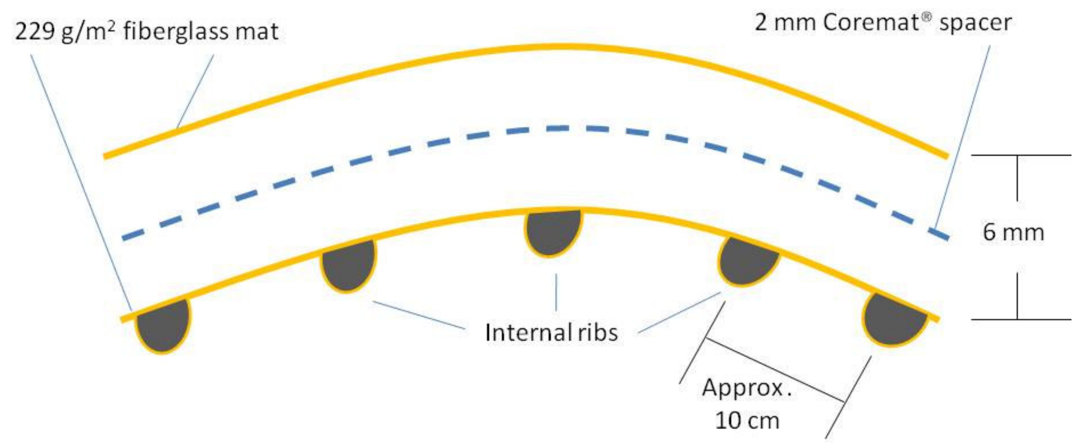


Figure 3.5. Cross section diagram of final carapace design with a 2 mm Coremat® spacer between two layers of 229 gram per square meter fiberglass mat and internal rib structure.

Figure 3.6. Left: prototype synthetic carapace. Right: synthetic sea turtle carapace featuring a layer of fiberglass cloth on each side of a Coremat® spacer used for sea turtle/ boat collision testing.

3.4 Detailed Description of Synthetic Design and Production.

The first step was to wrap the molds in cellophane to act as a release agent. Once the release agent was in place, the topside of the mold was sprayed with a commercially available spray adhesive (Figure 3.7). The spray adhesive was used to keep the Coremat® layer in place while the polyester resin was applied. A single layer of Coremat® was laid on the mold and trimmed so that it would lay flat on the mold and form a single layer over the entire carapace, stopping approximately 1.5 centimeters beyond the edge of the mold. Once the Coremat® was placed, 237 cubic centimeters of polyester resin were mixed according to instructions (yellow pigment was added to increase visibility during testing), applied to the top of the Coremat®, and brushed on evenly so that all of the resin was absorbed by the Coremat® (Figure 3.8). Next, an approximately 1 square meter piece of fiberglass mat was placed on the Coremat® and trimmed so that it would lay flat on the carapace, forming a single layer of fiberglass that covered the carapace and extended past the end of the Coremat® layer to the edge of the mold. Once the fiberglass was in place, another 237 cubic centimeters of polyester resin was mixed and applied to the fiberglass. The resin was brushed on and spread out to evenly cover the entire fiberglass layer (Figure 3.8). Once the fiberglass layer had been completely covered, the mold was transferred to the curing area and allowed to cure at elevated temperatures for a period of at least 24 hours.

Figure 3.7 Left: carapace mold covered in cellophane wrap to act as a release agent. Right: spray adhesive being applied to the mold prior to application of the Coremat® layer.

Figure 3.8. Left: Resin being applied to the Coremat® layer. Right: Resin being applied to the first layer of fiberglass over the Coremat®.

After at least 24 hours had passed, the mold was retrieved from the curing area and the fiberglass carapace was removed from the mold. Any excess cellophane attached to the carapace was trimmed off and spray adhesive was applied to the underside of the artificial carapace. Then a length of 1.6 centimeter diameter foam rod (commonly used and referred to as backer rod) was cut to fit around the rim of the carapace, approx 1.5 centimeters inside the edge of the Coremat® layer (Figure 3.9). A second length of 1.6 centimeter foam backer rod was cut the length of and placed along the longitudinal axis of the carapace to act as a spine (Figure 3.9). Then 8 pieces of 1.3 centimeter diameter backer rod were cut to length and placed in at approximately equal distances along the spine, running from the spine to the backer rod around the rim acting as rib structures (Figure 3.9).

Once the ribs were in place, one layer of 229 gram fiberglass mat was placed over the ribs. This was done by either placing a large piece and trimming as needed to create one layer, or using large scrap pieces and fitting them together and trimming to create a single layer of fiberglass to cover the ribs (Figure 3.10). Along the edge, the fiberglass layer was extended past the Coremat® to be even with the previous fiberglass layer. Once the ribs and fiberglass were in place, another 237 cubic centimeters of resin were mixed and the resin was spread over the interior of the carapace, completely coating the fiberglass (Figure 3.10). Care was taken to not let the resin pool in the "bottom" of the overturned carapace and to ensure the resin was distributed as evenly as possible.

Figure 3.9. Left: backer rod being applied around the rim and along the longitudinal center of the underside of the carapace. Right: backer rod being cut and placed on the underside of the carapace from the center to the rim.

Figure 3.10. Left: fiberglass mat cut and placed over the rib structure. Right: resin being applied to the fiberglass on the underside of the carapace.

Once the resin was applied, the carapaces were kept upside down and placed into the curing area and allowed to cure for at least 24 hours. Following curing, any excess fiberglass was trimmed from the edge of the carapace and the carapace was considered complete. This process was repeated until the approximately 60 synthetic carapaces needed for field testing were complete. Periodically, a completed carapace was set aside (six total) and subjected to strength testing to assure the fabricated carapaces demonstrated the desired strength characteristics.

CHAPTER 4

DESIGN OF FIELD EXPERIMENTS

The field experimental program required the design and fabrication of approximately 60 synthetic carapaces as described previously, as well as a frame upon which to attach the carapace. A matrix of tests to be performed in the field was also developed, examining the effects of varying motor configuration, speed and depth of the model animal on the injuries experienced by the model carapace. Accelerometers were attached to each frame and video recording of each test was performed. This chapter provides the details of this process.

4.1 Frame Design

A frame was constructed to support the artificial carapaces for field testing. The frame had to be strong enough to support the artificial carapace in a manner similar to the body of an actual turtle, and have a similar size and weight. In addition, for practical reasons, the turtle frame needed to be easily repairable in the field, and not so rigid as to damage the boat or motor used during testing. Measurements made of sea turtles being rehabilitated at the Georgia Sea Turtle Center of similar size to the shells being used in testing and data from the literature (Hochscheid et al. 2003) indicated that the frame needed to weigh approximately 27 kilograms and be positively buoyant such that less than half the height of the carapace would be above the water surface when floating at rest.

A frame was constructed of 2.5 cm diameter PVC pipe and wrapped in closed-cell foam flotation material as shown in Figure 4.1. The PVC pieces were connected with common slip type couplings, and attached using sheet metal “zip” screws through the couplings to hold the PVC frame together. This allowed for rapid repair of broken frames in the field while maintaining buoyancy of the PVC frame. Attached to the PVC frame with stainless steel hose clamps was a 12 mm-thick piece of plywood, cut to the shape of the frame. Seventeen kilograms of lead dive weights were attached to the plywood with stainless steel hose clamps to add the necessary weight to the frame. A piece of flotation foam, molded to the shape of the carapace, was tied to the top of the frame above the wood with small rope. Three kilograms of lead weight were also added to the head piece to balance the model animal and allow the frame to float level in the water. Due to slight variations between each frame and buoyancy unit, each frame was tested to ensure the proper buoyancy, with slight weight and flotation changes made as needed. Five holes were drilled along the perimeter of the carapace (one at the rear, one on each side and one at each shoulder) and the carapace attached to the frame through these holes with plastic ties. Periodically, frames were damaged during testing and had to be repaired in the field before being re-deployed. Photos showing the frame, weights, and buoyancy unit can be seen in Figure 4.1.

Figure 4.1. Left: Underside of frame showing PVC frame, weights, flotation and head piece. Right: Broken frame being repaired in the field, buoyancy unit can be seen on top of frame.

4.2 Development of the Test Matrix

The testing procedures were designed to investigate the influence of a) boat speed, b) animal position in the water column, and c) vessel propulsion system on the frequency of fatal wounds in sea turtles during boat collisions. Boat/sea turtle collisions were simulated by placing a test specimen (a synthetic carapace attached to a test frame) in the water column and striking it with a small vessel. The various configurations of the tests are described below and summarized in Table 4.1.

The effect of different propulsion systems and propeller guards were examined. The standard configuration was a Honda® 90 horsepower four-stroke outboard motor on a 5.8 m Carolina Skiff®, which features a nearly planar underside and planes at speed. Two commercially available propeller guards were tested on this boat. The “Hydroshield®” is a small fin that is attached to the motor skeg just below the propeller. The “Prop Buddy®” is a large steel cage that attaches to the foot of the motor and encloses the propeller. The outboard motor used and the propeller guards tested can be seen in Figure 4.2.

Figure 4.2. Left: outboard motor on the Carolina Skiff. Right: Propeller guards clockwise from upper left, Fishing line guard, Prop Buddy®, Hydroshield®. Fishing line guard was not used during these tests.

A Mercury® 80 horsepower jet drive outboard motor was also mounted on the Carolina Skiff® for one series of tests (Figure 4.3). Another test series featured a 130 hp Sea Doo® personal watercraft (PWC, referred to here by the name commonly assigned to this class of vessels: “jet ski”) shown in Figure 4.3. Because the jet drive motor had already been installed on the Carolina Skiff by the time the decision was made to do a series of “floater” tests in which the animal floated higher in the water column, a 5.2 m Boston Whaler with a 90 hp Honda outboard motor with standard propeller was used for this test series (described below).

Figure 4.3. Left: Foot of jet outboard motor. Right: Sea Doo® "jet ski" used for tests.

Three speeds were chosen for testing: idle, sub-planing, and planing. Idle speed is when the motor is in gear but idling. This is the slowest a boat can steadily travel and is most commonly used near marinas and when passing through “No Wake” zones. The idle speed of the Carolina skiff with the outboard and no propeller guard was approximately 7 km/hr. This speed was used as “idle speed” for all other motor configurations and propulsion types.

Planing is defined as the condition where a boat skims across the water with only a small portion of the hull in the water. A planing speed of 40 km/hr was chosen for the field tests.

Sub-planing is defined as a speed just below the minimum planing speed. As a vessel goes from idle to planing, or vice versa, it will pass through a sub-planing speed, where fuel consumption per distance travelled is typically much higher, and wake production is maximized, at least for the small vessels considered here. Therefore, most recreational boaters spend very little time traveling at sub-planing speed, as defined here. For the field tests, the vessel was moving at approximately 14 km/hr when at sub-planing speed.

The turtles were placed at two different depths in the water column: at the surface and at propeller depth. As noted above, sea turtles often spend most of the day foraging in shallow, nearshore areas and have been observed moving between the surface and shallow depths of less than one meter. Because of this behavior, the chance of interaction with recreational vessels is increased. For a surface test, the animal was tethered to an anchor to maintain horizontal position, but allowed to float, resulting in about half the carapace visible above the surface. For tests at propeller depth, the top of the carapace was positioned 48 cm below the water surface (the depth to the center of the propeller measured with the boat at rest).

Deceased animals often fill with gas as a result of decomposition and float at the surface with the majority of the animal's carapace visible above the surface. To simulate these conditions, all but nine kilograms of lead weights were removed from the frame, and all the weight was removed from the head piece to allow it to float with almost the entire carapace above the water surface. These tests are referred to as "floater" tests. The purpose of these tests were to determine if a dead floating sea turtle carcass could sustain injuries similar to those seen on stranded sea turtles.

Table 4.1. Propulsion system, speed, and animal placement configurations for field tests. "Standard" propulsion system means conventional outboard motor with propeller and no guard. Hydroshield® and Prop Buddy® are two types of guards attached to standard outboard motor. Idle speed is defined at 7 km/hr, sub-planing is 14 km/hr, and planing is 40 km/hr. Prop depth means depth to the center of the propeller when at rest.

Test Series	Vessel	Propulsion System	Animal Position	Speed	Number of trials
1	Carolina Skiff	Standard	Surface	Idle	5
2	Carolina Skiff	Standard	Prop Depth	Idle	5
3	Carolina Skiff	Standard	Surface	Sub-Planing	11
4	Carolina Skiff	Standard	Prop Depth	Sub-Planing	5
5	Carolina Skiff	Standard	Surface	Planing	5
6	Carolina Skiff	Standard	Prop Depth	Planing	5
7	Carolina Skiff	Hydroshield®	Prop Depth	Idle	5
8	Carolina Skiff	Hydroshield®	Prop Depth	Planing	5
9	Carolina Skiff	Prop Buddy®	Prop Depth	Idle	5
10	Carolina Skiff	Prop Buddy®	Prop Depth	Planing	4
11	Carolina Skiff	Jet Outboard	Surface	Idle	5
12	Carolina Skiff	Jet Outboard	Prop Depth	Idle	5
13	Carolina Skiff	Jet Outboard	Surface	Planing	5
14	Carolina Skiff	Jet Outboard	Prop Depth	Planing	5
15	Sea Doo	Inboard Jet	Surface	Idle	5
16	Sea Doo	Inboard Jet	Prop Depth	Idle	5
17	Sea Doo	Inboard Jet	Surface	Planing	5
18	Sea Doo	Inboard Jet	Prop Depth	Planing	5
19	Boston Whaler	Standard	Floater (surface)	Planing	5

4.3 Testing Procedures

A suitable site was needed to perform the field tests. The site needed to be relatively shallow and have a sandy bottom to allow easy access for workers to deploy and retrieve animals before and after testing. Absence of tidal and wave effects was also preferred to reduce the number of variables and make the testing procedures safer and easier. Most suitable sites along the coast were in high-traffic areas with swimmers or recreational boaters, and strong tidal effects, and were therefore deemed unsafe for the tests.

Most inland lakes and ponds in the area are privately owned and permission to use these sites could not be readily acquired. Permission was granted by Effingham County, Georgia, to perform field tests in an abandoned sand quarry owned by the county. This spot was remote, off-limits to the general public, and allowed relatively easy access to deploy the models.

To deploy the animals at the proper depth, an anchor was deployed at a water depth of approximately three meters. A length of nylon line was run from the shore through a pulley attached to the anchor. The end of the line was attached to a bridle on the bottom of the frame (made of 50-pound test fishing line) to which the turtle carapace was attached. This allowed the location (horizontal and vertical) of the test sample to be maintained from the shore. Slight tension was kept on the line throughout the test to keep the animal in place, with care taken not to restrict the movement of the animal at the moment of impact any more than necessary. For the propeller depth tests, two lengths of fishing line with fishing floats positioned at the proper length were attached to the top of the carapace. The animal was pulled under water until the floats were at the surface and held at that depth throughout the test. Once the test was complete, the animal was retrieved and a new carapace and frame was deployed in its place for the next test. Figure 4.4 shows the design of model animal deployment and Figure 4.5 shows a test specimen deployed awaiting the start of a test and a damaged carapace being retrieved.

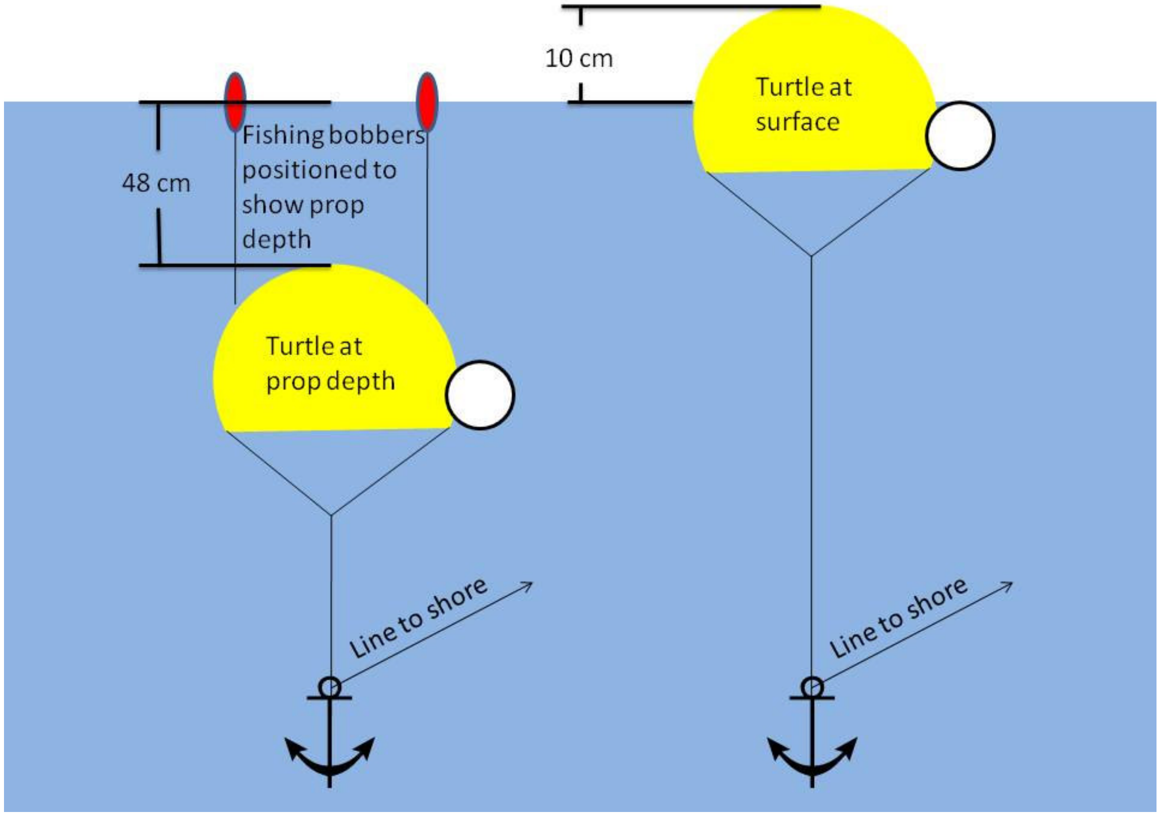


Figure 4.4. Model animal positioning for surface and propeller depth tests.

Figure 4.5. Left: a synthetic sea turtle carapace and frame deployed for a "surface" test. Right: a damaged carapace and frame retrieved after test run.

Performance of the field tests required eight people to carry out all of the required tasks. Two people were positioned in the boat, a boat operator and an observer in the bow of the boat to record the orientation of the specimen as the boat approached. It was found to be beneficial that two people work together on specimen deployment, retrieval, and position in the water column during the tests. Two additional people were in charge of frame repair, preparation of models prior to deployment (attaching the carapace to the frame), and attachment, activation, and downloading data from the accelerometers attached to the frame. One person was charged with note-taking and one person was responsible for photographing carapace damage upon retrieval of specimen and video recording of the tests.

4.4 Data Collection

A variety of data types were collected from each test. The position and orientation of the test sample relative to the boat at the instant of collision was noted and recorded. A numerical code was used to record the turtle orientation as the boat approached. The positions were numbered from one at the head, clockwise around to four on the left side (Figure 4.6). For example, if the boat was approaching the animal from behind, the boat orientation would be recorded as “three”. Combination numbers were used (i.e. 1-2) if the boat approached between two of the numbered positions. This nomenclature was also used in describing the position of wounds found on the carapace. Once the carapace was retrieved, it was photographed and any damage noted on a data sheet. The data sheet used can be found in Appendix B.

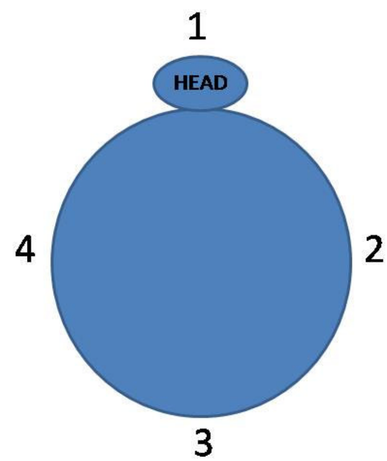


Figure 4.6. Orientation codes used to describe the strike direction of the boat and the location of damage to the carapace.

Accelerometers were attached to the frame to record the three-axis acceleration of the model during the tests. Data from these accelerometers could be used to determine position and force experienced by the animal during vessel impact. To help determine the rotation and motion of the test specimen during impact, two Onset HOBO Pendant G® data loggers were attached to the test frame; one near the head and one near the center of mass. These loggers were set to sample at 100 Hz, allowing 3 seconds of data to be recorded per test.

Video records of most tests were recorded from a camera positioned on shore near the test site. The distance of the camera from the animal during tests, and the fact that the specimen was under the boat and out of view at time of impact limited the usefulness of the video data. Underwater video was attempted, but the turbidity of the water, along with the steep slope of the ground at the test site, made filming underwater impossible with the available equipment.

CHAPTER 5

RESULTS FROM FIELD EXPERIMENTS

The primary hypothesis defined for investigation via the study described here is: Does the type of propulsion system, presence of propeller guards, or boat speed influence frequency of fatal injuries in sea turtle strikes? The tests were performed with models, and it is not possible to know with certainty whether a particular level of damage would be fatal. But the photographs of real turtles killed in boat strikes provide guidance.

A “catastrophic” injury is defined here as an injury with a high likelihood of fatality. Any wound that penetrated the carapace was considered catastrophic since any penetration of the carapace generally results in the compromise of the coelomic cavity resulting in infection and ultimately death (M. Dodd, pers. comm.). The exception is any small slicing wounds on the margin or posterior of the carapace less than 4 cm in length. In this case, the shell and bone extend beyond the edge of the body cavity and small wounds in this area are less likely to penetrate the coelomic cavity (M. Dodd, pers. comm.). It should be noted that the edge of the artificial carapace may be thinner, or more brittle and prone to tearing, than the interior of the model carapace, or the real carapace. Laboratory testing did not include tests of edge material.

Several of the tests resulted in severe damage to the frame, suggesting possible injury to the animal, but displayed no damage to the carapace. While damage to the frame was noted, the frame was not designed to match any specific structural characteristics, and therefore any damage to only the frame cannot be positively classified as catastrophic. Boat orientation (described in Chapter 4.4) was also recorded as the boat approached the test specimen. These data are noted in the following tables, but the data were not analyzed for effects of orientation on damage type or severity.

The wounds on each model carapace were categorized using the above criteria. When damage to the carapace was observed, it was typically parallel slicing wounds from the propeller, blunt force wounds from the skeg or another piece of the outboard motor foot where a section of the carapace was torn away, or a combination of the two. Propeller wounds were measured as a straight distance end to end (not following the sigmoid curve of the cut). These lengths were then summed to get a total cut length for each carapace. The composite material used in the synthetic carapaces has a tendency to tear at 90 degree angles from the ends of propeller cuts; these areas were not included in the quantification of the wound severity. Figure 5.1 shows a typical carapace with propeller cuts, showing the cut from the propeller and the tearing of the composite material.

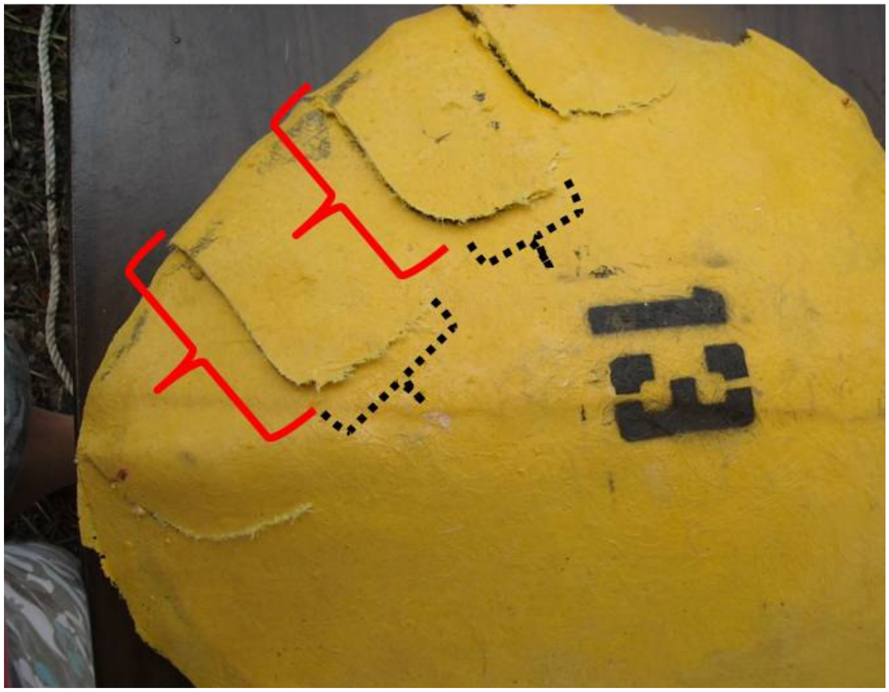


Figure 5.1. Example of propeller cut wound observed during tests. The solid brackets represent cut length measured. The dashed brackets show the area of tearing of composite material not included in the cut length calculations.

Section loss wounds from blunt force impact were measured and the area lost was approximated by fitting the measurements to basic geometric shapes. Figure 5.2 shows examples of blunt force wounds observed. Columns 4 and 5 in Table 5.1 show the length of propeller cuts and/or the percentage of total area a section loss represents; column 6 indicates whether the wounds observed were characterized as catastrophic. A complete table of all tests along with comments collected on the data sheets can be found in Appendix C. Photographs from all of the field experiments appear in Appendix D. Below, the results of each type of test are described, along with a discussion of accelerometer data.

Figure 5.2. Examples of blunt force wounds observed in test samples.

5.1. Standard Motor Configuration

5.1.1 Idle Speed, Surface

Results from tests performed with the standard motor configuration at idle speed and the test specimen positioned at the surface show that it is possible to penetrate the carapace even at idle speed. Two of the trials show no visible damage or only minor scrapes on top of the carapace, while other trials show propeller wounds that penetrate the carapace. The lengths of the propeller cuts totaled 10.6 cm and 11.7 cm for the two damaged carapaces. These trials were considered catastrophic using the criteria specified above. There was no area of blunt force impact evident in these tests. Results from these tests are shown in Table 5.1 and photographs of the carapaces tested in this series are shown in Figure 5.3.

Table 5.1. Results from tests performed with **standard motor configuration**, at **idle speed**, with test specimen at the **surface**. “Total length of cuts” refers to total length of cuts from parallel slicing wounds. “Percent of Total Area Damaged” refers to percentage of area damaged from blunt force wounds. “NA” indicates that type of injury is not applicable to that trial. Wounds that were judged to be catastrophic are indicated with an “X.” Animal orientation defined in Figure 4.3.

Carapace Number	Boat Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
1	6.5	2-1	NA	NA	
2	7.0	4	11	NA	X
3	6.5	3-4	5	NA	X
4	6.6	3	NA	NA	
5	7.0	3-4	12	NA	X

Figure 5.3. Model carapaces after tests with **standard motor configuration**, no propeller guard, **idle speed**, with the test specimen at the **surface**. Damage to the carapace is circled in red.

Idle Speed, Propeller Depth

With the model animal moved to propeller depth, three of the five tests performed at idle speed with the standard boat configuration resulted in no visible damage and a fourth showed only minor damage along the edge. However, one test displayed propeller cuts that penetrated the carapace, the resulting wound lengths were greater than the 4 cm required to be considered catastrophic. Results from these tests are shown in Table 5.2 and Figure 5.4.

Table 5.2. Results from tests performed with **standard motor configuration**, **idle speed**, with model animal at **propeller depth**. See Table 5.1 for definition of terms.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
6	6.5	2	2	NA	
7	6.2	4	NA	NA	
7	6.3	3	NA	NA	
8	6.4	4-1	NA	NA	
9	7.2	3-4	NA	NA	
10	6.6	1-2	15	NA	X

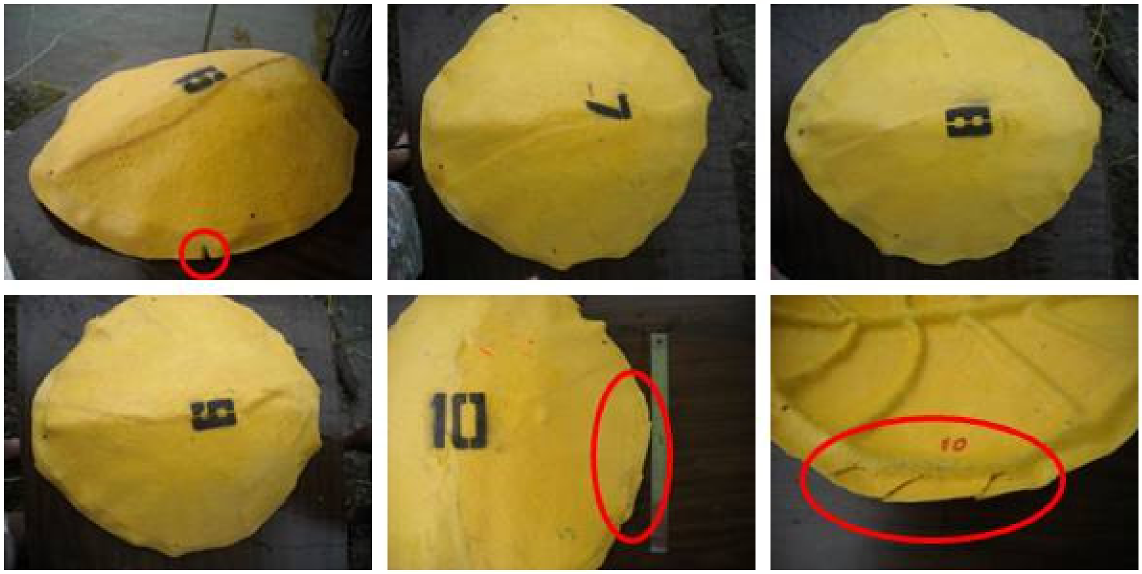


Figure 5.4. Results from tests with **standard motor configuration**, **idle speed**, and model at **propeller depth**.

Sub-Planing Speed, Propeller Depth

At sub-planing speed, it was noticed that a large bow wave was produced. It is suspected, although not directly observed, that this bow wave changed the attitude of the animal as the boat approached. Despite this, the tests run at this speed with the model animal at propeller depth and standard motor configuration, four of the five carapaces received some type of damage to the carapace. While the fifth test showed no visible damage to the carapace, the frame from this test was damaged, suggesting that the attitude of the specimen was changed as the boat passed. Damage to the frame was noted in two of the other tests from this group. Three of the five carapaces tested received damage that would be classified as a catastrophic injury. Table 5.3 and Figure 5.5 show results from these tests.

Table 5.3. Results from tests performed with **standard motor configuration**, **sub-planing speed**, with test specimen at **propeller depth**. See Table 5.1 for definition of terms.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
11	15.5	3-4	NA	NA	
12	17.9	1-4	8	NA	X
13	14.9	4	53	1%	X
14	14.0	3	10	NA	X
15	15.2	3	3	NA	

Figure 5.5. Tests with **standard motor configuration**, **sub-planing speed**, and model animal at **propeller depth**. Lower right shows damage to the frame during test number 12.

Sub-Planing Speed, Surface

Two carapaces showed catastrophic propeller cuts on the edge from the tests run with the normal motor configuration, sub-planing speed and the test specimen at the surface. Two other tests resulted in contact, but showed no visible damage to the carapaces. Six passes over the fifth carapace resulted in no contact, believed to be a result of the bow wave mentioned in the previous section pushing the animal away from the motor. Table 5.4 shows results from these tests. Figure 5.6 shows pictures of the carapaces tested in this series.

Table 5.4. Tests with **standard motor configuration**, **sub-planing speed**, with model animal at the **surface**. See Table 5.1 for definition of terms. Vessel speed and orientation were not recorded for the second trial with shell number 19. This is noted as “NA” in the table below.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
16	15.4	2	27	NA	X
17	14.3	4	50	NA	X
18	13.9	1-4	NA	NA	
19	15.4	2-3	NA	NA	
19	NA	NA	NA	NA	
20	16.3	2-3	NA	NA	
20	16.2	1-2	NA	NA	
20	15.9	1	NA	NA	
20	15.4	1	NA	NA	
20	15.5	2	NA	NA	
20	14.0	4	NA	NA	

Figure 5.6. Tests with **standard motor configuration**, **sub-planing speed** and model animal at the **surface**.

Planing Speed, Propeller Depth

All five carapaces used in the subsequent series (normal motor configuration, planing speed, animal at propeller depth) had numerous propeller cuts on the top of the carapace and/or blunt force damage that penetrated the carapace. In addition, four of the five carapaces showed a single blunt force wound at a 90º angle to the parallel slicing wounds from the skeg of the outboard motor. All of these injuries met the criteria used to classify damage as catastrophic. These results indicate a high likelihood of turtle fatality from a collision under these conditions. Table 5.5 and Figure 5.7 show the results from these trials.

Table 5.5. Tests performed with **standard motor configuration**, **planing speed** with model animal at **propeller depth**. See Table 5.1 for definition of terms.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
22	44.2	2-3	80	<1%	X
23	40.1	3	12	6%	X
24	41.5	3-4	40	NA	X
25	42.7	3-4	101	8%	X
26	42.0	3-4	36	2%	X

Figure 5.7. Results from tests with **standard motor configuration**, **planing speed** and model animal at **propeller depth**.

Planing Speed, Surface

Damage was severe when the animal was moved to the surface and struck at planing speed with the conventional propulsion system. All five carapaces displayed blunt force damage that penetrated the carapace and were classified as catastrophic. In one test, the extent of the blunt force damage was 33% of the entire surface area of the carapace. Also, major frame damage was noted in three of the five tests. Only one carapace displayed clear propeller cuts in addition to a blunt force wound. The increase in speed resulted in much more severe and consistent damage than the surface tests at idle speed. All tests performed at planing speed with the standard outboard motor resulted in catastrophic injuries. Table 5.6 and Figure 5.8 show results from this test series.

Table 5.6. Tests with **standard motor configuration**, **planing speed**, with model animal at the **surface**. See Table 5.1 for definition of terms.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
21	41.7	1	NA	33%	X
27	40.1	1-2	NA	6%	X
28	41.6	1-4	NA	4%	X
29	42.7	1	41	6%	X
30	41.6	3	NA	4%	X

Figure 5.8. Results from tests with **standard motor configuration**, **planing speed** and model animal at the **surface**.

High Buoyancy Model, Planing Speed, Surface

Animals are sometimes observed floating higher in the water column after death than are typically observed while still alive. A final series of field tests was done to see if the damage from a conventional outboard motor was different when the relative draft of the animal decreased. The purpose of this test was to determine whether boat collision injuries documented in stranded sea turtles could have occurred post-mortem while the carcass was floating on the surface. Weight was removed from the test animal until the carapace was floating with the majority of the carapace above the surface. These tests were done at planing speed with a 5.2 m Boston Whaler with a 90 hp Honda 4-stroke outboard motor with a conventional propeller and no guard. The hull of the Boston Whaler has a different shape than the Carolina Skiff used in the other tests. The Boston Whaler hull has a cathedral hull with a “V” in the center and smaller “V” features on both chines, whereas the bottom of the Carolina Skiff is nearly planar and horizontal.

Four of the five tests on the “floaters” resulted in major damage to the carapace and/or frame. The fifth test showed no damage to the carapace, but the frame did sustain damage. The damage was not obviously different from that observed with the earlier surface tests designed to investigate what happens to a live animal on the surface. Results are shown in Table 5.7 and Figure 5.9.

Table 5.7. "**Floater**" tests performed with **standard motor configuration**, at **planing speed**. See Table 5.1 for definition of terms. This series of tests was performed with a 5.2 m Boston Whaler and a conventional outboard motor.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
1	40	3	10	15%	X
3	43.2	1-2	NA	4%	X
4	38.5	3	27	5%	X
5	39.2	2	NA	NA	
6	42.5	4	NA	15%	X

Figure 5.9. Results from "**floater**" trials at **planing** speed.

5.2. Outboard Motor with Propeller Guards

Hydroshield, Idle Speed, Prop Depth

The tests described above provided a baseline, by demonstrating what could be expected with a conventional outboard motor at three different speeds and two different depths. The next series of tests were designed to investigate the benefits associated with the use of either of two commercially available propeller guards. One, the Hydroshield®, is a horizontal fin that is bolted to the skeg of a conventional outboard motor below the propeller (Figure 4.2 and Figure 5.11). Four of the five tests performed with the Hydroshield® on the outboard motor, at idle speed, with the test specimen at propeller depth, resulted in only minor tears/scratches in the composite material. The fifth test displayed propeller cuts on the edge that penetrated the carapace. The total length of the cuts on that carapace was 20 cm, enough to classify the damage as catastrophic. These results were comparable to the results found with the standard motor configuration at idle speed, with the benefit of possibly reducing the chance of propeller cuts by shielding the animal from contact with the propeller. Results are presented in Table 5.8 and photographs are shown in Figure 5.10.

Table 5.8. Tests with the **Hydroshield®**, at **idle speed**, with the model animal at **propeller depth**. See Table 5.1 for definition of terms.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
31	6.5	2	NA	NA	
31	6.3	3	NA	NA	
31	6.3	1	NA	NA	
31	6.4	2	20	NA	X
32	7.0	2	NA	NA	

Figure 5.10. Results from tests with the **Hydroshield®**, at **idle speed**, with model animal at **propeller depth**.

Hydroshield, Planing Speed, Propeller Depth

All five tests performed with the Hydroshield® on the motor, at planing speed and with the model animal at propeller depth, resulted in catastrophic carapace damage. Three carapaces had large puncture wounds from blunt force contact. The other two showed large areas of parallel propeller wounds penetrating the carapace. Results are comparable to tests run at with the standard outboard configuration as far as the likelihood of fatality. However, these tests displayed more blunt force wounds than observed with the standard configuration. There was a small, sharp piece of the Hydroshield® that protruded from the front of the skeg (Figure 5.10) that appeared to cause some of the damage. Table 5.9 and Figure 5.12 show the results.

Figure 5.11. Hydroshield® installed on outboard motor. Circle highlights the edge protruding from front of motor skeg.

Table 5.9. Tests performed with the **Hydroshield**®, at **planing speed** with model animal at **propeller depth**. See Table 5.1 for definition of terms.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
32	41.2	1	150	10%	X
33	40.7	3-4	74	NA	X
34	40.7	1-4	NA	<1%	X
35	39.8	2-3	NA	<1%	X
36	38.7	1-4	NA	28%	X

Figure 5.12. Results from the tests with the **Hydroshield®**, at **planing speed** and model animal at **propeller depth**.

Prop Buddy, Idle Speed, Propeller Depth

A second, commercial propeller guard was also tested. The Prop Buddy® is essentially a stainless steel cage that surrounds the propeller (Figure 4.2). All five idle speed tests with the Prop Buddy®, with the model animal at propeller depth, resulted in no visible damage to the carapace. This suggests that the Prop Buddy® may provide better protection for the animal from propeller cuts at idle speeds compared to the standard motor configuration (one catastrophic injury in six trials) under the same conditions.

Prop Buddy, Planing Speed, Propeller Depth

Only four planing speed tests were performed with the Prop Buddy® and model animal at propeller depth, since model frames were broken beyond repair in the field after these four tests. All four tests resulted in tear-out of a section of the carapace from blunt force contact. The area of damage ranged from 4.9% to 11.1% of the total area of the carapace (Table 5.10, Figure 5.13). The cage around the propeller prevented the characteristic parallel slicing wounds from the propeller, but the larger effective projected area of the motor foot resulted in increased catastrophic blunt force damage. These results are numerically comparable to the results from the same conditions with the standard outboard, however the catastrophic wounds seen here are solely from blunt force as opposed to propeller wounds observed with the standard motor configuration.

Table 5.10. Tests with the **Prop Buddy®**, at **planing speed**, with the test specimen at **propeller depth**. See Table 5.1 for definition of terms.

Carapace Number	Speed (km/h)	Initial Boat Orientation	Total Length of Cuts (cm)	Percent of Total Area Damaged	Catastrophic
37	39.7	4	NA	11%	X
38	41	1	NA	9%	X
39	42	1-2	NA	11%	X
40	40	1	NA	5%	X

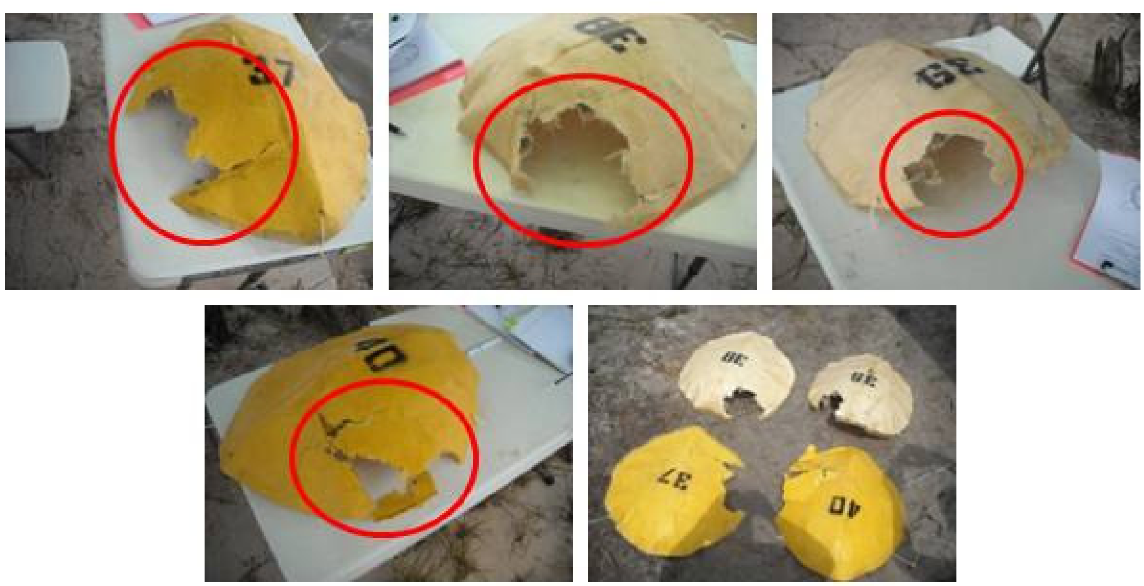


Figure 5.13. Results from tests with the **Prop Buddy®,** at **planing speed**, with model animal at **propeller depth**.

5.3. Jet Outboard Motor and PWC

Jet Outboard, Propeller Depth, Idle and Planing Speeds

For this series of tests, the model animal was positioned at the propeller depth of the standard outboard configuration, as in previous propeller depth tests. However, the foot of the jet outboard did not reach into the water as far as the standard outboard. Therefore, all tests with the jet outboard motor, and the model animal at propeller depth, resulted in no visible damage to the test carapace. Only one test resulted in any contact with the specimen, at idle speed, when the model animal was not positioned deep enough in the water column. This contact resulted in no visible damage to the carapace. There was no contact with the specimen in the other tests.

Personal Watercraft, Propeller Depth, Idle and Planing Speeds

Similarly, the PWC has a draft of only a few centimeters and the intake is almost flush with the hull bottom. With the model animal positioned at the propeller depth of the standard outboard configuration, the PWC passed over the specimen resulting in no contact in any of the tests.

Jet Outboard, Surface, Idle and Planing Speeds

When the model animals were moved to the water surface, the jet outboard inflicted some damage, but much less than had been observed with the conventional motor with or without the propeller guards. At idle speed, no damage was visible on any of the carapaces. At planing speed, scrape marks from the jet intake were visible on the top of the carapaces, but no portion of the carapace was penetrated and none of the damage was considered catastrophic.

Personal Watercraft, Surface, Idle and Planing Speeds

The results with the PWC and the animal deployed on the surface were even more favorable. As installed (per manufacturer instructions), the rear of the intake for the jet outboard projects below the hull of the boat. The intake made contact with the carapaces resulting in scrape marks but no catastrophic damage. The PWC intake is smoother and more "cleanly" integrated into the hull and did not result in this type of scraping. No damage was visible to any of the carapaces for the idle speed tests with the PWC. At planing speed, only scrape marks were evident on the top of the carapaces, and they were less pronounced than with the jet outboard. No portion of the carapace was penetrated and none of the damage was considered catastrophic.

5.4. Accelerometer Data

Two accelerometers were attached to the model frames to determine acceleration at impact for many of the experiments. From these data, velocity, orientation, and distance traveled could then be computed. The sampling rate on the accelerometers was set to 100 Hz. Examining the data collected from the accelerometers, it can be seen that the duration of the impact was typically on the order of 0.1 seconds. The Onset Computer Pendant G® loggers used have a maximum acceleration range of ±3G along each axis. Processing and extensive examination of the data revealed that this 3G limit was exceeded along at least 1 of the 3 axes on every test where contact was made with the specimen. Since the data limits were exceeded in each test, it is not possible to get reliable results from the reported data. In addition, acceleration is used to calculate tilt angle along each axis. To do this, the loggers truncated any acceleration values with magnitude greater than one. It is clear from data examination that in all instances where the acceleration exceeded 1 G along any axis, the tilt angle along that axis was unreliable. Therefore, reported tilt data at accelerations above 1 G were unusable.

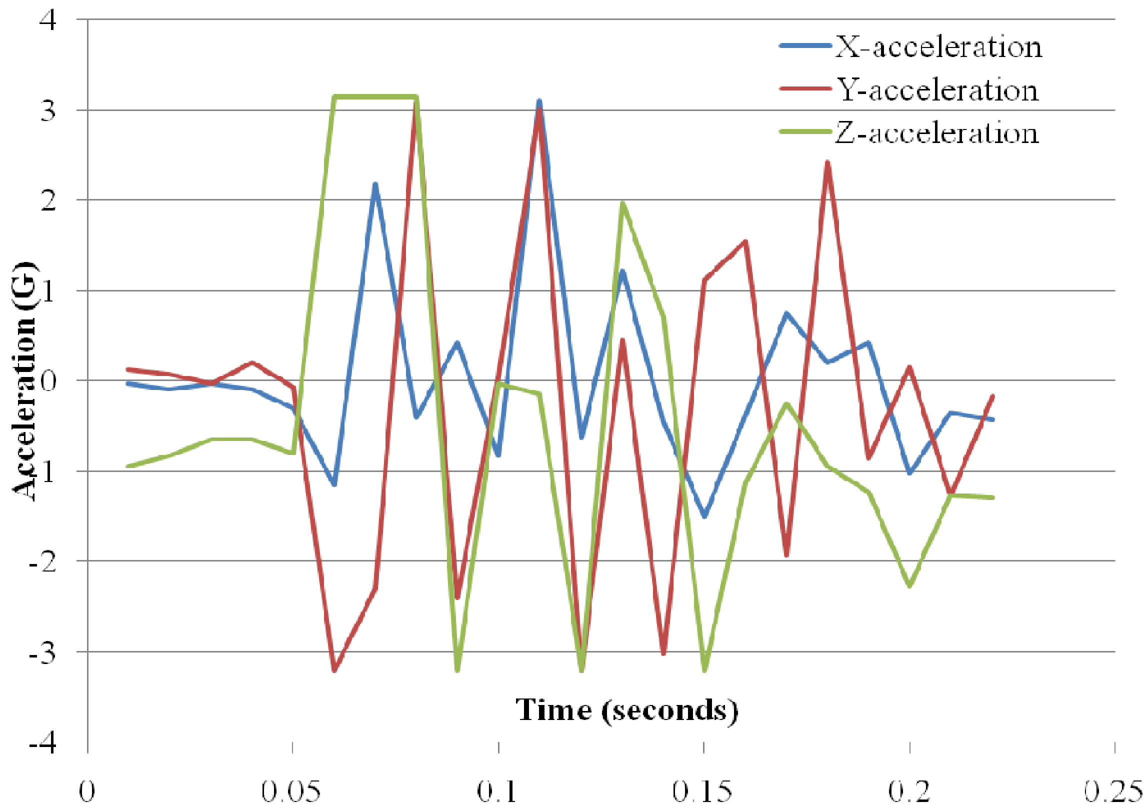


Figure 5.14. Sample graph showing acceleration in the x-, y-, and z-directions recorded by the accelerometers. Sampling rate was 100 Hertz.

Because the range of the sensors was exceeded on each test, little useful information can be obtained from the accelerometer data. In future tests, it is recommended that accelerometers with a larger range and higher sampling rate be used. Because the range of the sensors was exceeded in all tests, it is hard to estimate the maximum range needed to accurately record all of the motion that occur at impact. Analysis of the data led to the recommendation that in future testing accelerometers be used that have a maximum range of ±10G and a sampling rate of 200 Hertz in order to better capture the motion of the animal at impact.

5.5. Statistical Analysis

Statistical analysis of the data was performed to determine if speed, depth in the water column, and outboard configuration contributed to the likelihood of a catastrophic injury. A Chi-squared contingency table analysis was considered for analysis of frequencies. However, because of the small sample size here, the results from a Chi-squared test could be considered misleading (Kirkman, 1996). The Fisher, Freeman, Halton exact test is more suitable for data with small sample sizes and was therefore used here (Kirkman, 1996).

The Fisher, Freeman, Halton exact test is similar to the Chi-squared in that a contingency table of expected values is calculated for each analysis. The probability of this contingency table appearing among all possible tables with both the same row totals and same column totals is calculated, along with the probability of all other tables in this "universe." The probability of the contingency table is summed with the probability of each less probable table to compute the p-value (Kirkman, 1996). For these tests, p-values of less than 0.05 indicate that the two variables are not independent of each other (rejecting the null hypothesis), while p-values greater than 0.05 indicate that the independent variable does not have a direct effect on the dependent variable (accepting the null hypothesis). A 2x2 and 2x3 contingency table was used to test the hypothesis of independence for depth in the water column and speed of the vessel, respectively. These tests were performed using STATXACT8® (Cytel Statistical Software Inc).

For the standard motor configuration, statistical analysis showed that the likelihood of catastrophic damage was independent of animal depth in the water column (assuming the animal is shallow enough to be hit) (Fisher Statistic = 0.549, DF = 1, p = 0.516) but was dependent on the speed of the vessel (Fisher Statistic = 13.6, DF = 2, p =

0.001). The field tests performed on the two types of propeller guards were only run on specimens at propeller depth. This approach was chosen because propeller guards were designed to cover the propeller, and therefore it was assumed that only propeller depth tests would be affected significantly. According to the statistics presented above, this is acceptable because depth does not affect the chance of catastrophic injury. Similarly, a statistical comparison of the propeller guards showed that with both the Hydroshield® (Fisher Statistic = 6.15, DF = 1, $p = 0.048$) and the Prop Buddy® (Fisher Statistic = 8.44, DF = 1, $p = 0.008$) in place, the chance of a catastrophic injury is dependent on the vessel speed. Higher vessel speeds resulted in more catastrophic damage. For both of the jet drive propulsion types (jet outboard and jet ski), statistical analysis showed that the chance of catastrophic injury is not dependent on either speed or depth ($p = 1.00$) as no catastrophic injuries were observed in these tests.

Looking at damage severity versus speed (ignoring motor type and depth), statistical analysis shows that the likelihood of a catastrophic injury is dependent on speed (Fisher Statistic = 12.38, DF = 1, $p = 0.001$); higher speeds increase the chance of catastrophic injury. Similar analysis of likelihood of catastrophic damage versus depth (this time ignoring motor type and vessel speed) revealed that these two variables are not directly related (Fisher Statistic = 1.24, DF = 1, $p = 0.369$); position in the water column does not affect the chance of catastrophic injury, assuming the animal is shallow enough to be hit. A third test ignoring speed and depth and directly comparing severity of damage to the five propulsion types tested showed a strong correlation between these two variables (Fisher Statistic = 35.3, DF = 4, $p = 8.86e\text{-}8$) showing that the type of propulsion system does affect the chance of catastrophic injury.

In summary, the statistical analysis reveals that vessel speed and propulsion type affect the likelihood of catastrophic injury. A standard motor, with or without propeller guards, yields a high likelihood of causing catastrophic injuries at high speeds. At low speeds, this chance of catastrophic injury is reduced. Statistical analysis also suggests that the position of the animal in the water column does not affect the probability of a catastrophic injury. This is consistent with intuition and the conclusions drawn from initial inspection of results.

CHAPTER 6

CONCLUSIONS

Interactions with marine vessels represent one of the greatest threats to loggerhead sea turtles. Yet prior to the study described here, no one had investigated whether simple modifications to small boats or their mode of operation would influence the type of damage or the likelihood of fatal damage when a vessel hits an animal in the field.

The tests described in this report required the development and fabrication of approximately 60 artificial sea turtle carapaces possessing similar tensile strength characteristics to those of real animals. Frames were also fabricated to provide a base to which to attach the model carapaces, and to achieve the proper buoyancy and weight. The final design had a size, mass, and specific gravity similar to a real animal.

Field tests were performed in calm water with the model animals tethered in place. Boat/ sea turtle collisions were simulated with a nearly flat-bottomed, 5.5 m Carolina Skiff boat with a conventional outboard motor with a standard three-bladed propeller, both with and without either of two commercially available propeller guards, and with a jet outboard motor installed in place of the conventional outboard motor. Another series of tests was performed with a personal watercraft (PWC). Tests with each vessel were conducted at idle speed (7 km/hr), sub-planing speed (14 km/hr), and planing speed (40 km/hr). Animals were deployed at both propeller depth and on the water surface.

With the standard motor configuration (outboard motor with no guard over the propeller), decreasing the speed of the boat from planing to idle speed decreased the chance of a catastrophic wound by 60%. At idle speed, four of the ten trials resulted in catastrophic wounds, compared to ten of ten at planing speed. The sub-planing speed yielded five catastrophic wounds, and several sub-planing trials were conducted where no contact was made between the boat and the animal. This appeared to be the result of the large bow wave being created by the boat, which may have pushed the animal away from the propeller before it could be struck.

The two tested propeller guards (Hydroshield® and Prop Buddy®) provided some benefit by reducing the likelihood of propeller cuts when the boat was traveling at idle speed (one out of five tests at idle speed with the Hydroshield resulted in propeller cuts, zero of five with the Prop Buddy, versus two out of five with the standard motor configuration). At planing speeds, however, the guards resulted in catastrophic damage in every case. Both provide some protection from the spinning propeller, but both also increase the projected area approaching the animal. The result was a more significant occurrence of what was termed blunt trauma (100% occurrence at planing speed).

Two types of jet propulsion were considered. The same Carolina Skiff used for most of the tests with the conventional motor was outfitted with a jet outboard. The jet outboard features a lower unit with an intake covered by a grill. The motor was installed per manufacturer recommendations, which placed the forward end of the intake grill slightly above the bottom of the boat's transom, and the rear portion of the grill slightly lower (approximately 10 cm) than the bottom of the transom. The result was that a portion of this grill would slide over the animal for the tests done on the surface, resulting in some scraping damage but no damage that was classified as catastrophic. Tests conducted with the jet outboard where the model animal was deployed at propeller depth resulted in no damage to the model carapace.

The PWC tests were similar to the jet outboard, except that the intake for the jet on the PWC is more smoothly integrated into the hull of the vessel and the resulting scrapes on the model animals were less significant. None of the tests with the jet outboard or the PWC resulted in catastrophic wounds. However, it should be noted that the synthetic carapace was designed primarily for correct tensile strength as opposed to overall structural strength. Therefore, it may be possible that some of the non-catastrophic tests would have resulted in crushing damage not observed with this carapace design.

An additional series of tests were conducted with a conventional outboard motor at planing speed colliding with a turtle that was floating higher in the water column than typically occurs with a live animal, to determine if post-collision examination could reveal whether an animal had been floating higher, as is common after death, prior to the collision. It has been argued that many of the vessel related injuries seen in stranded sea turtles were the result of post-mortem impacts. It was concluded, based on the comparison of five tests using a high buoyancy model to the surface tests, all with the standard motor configuration, that a dead floating carcass sustains blunt force injuries similar to those observed with the standard model floating on the surface at planing speed.

Statistical analysis of the data revealed that the chance for a catastrophic injury is influenced mainly by 1) motor type and configuration and 2) speed of the vessel. It was shown that depth of the specimen in the water column had little or no influence on the chance of catastrophic injury due to a boat collision (as long as the specimen is close enough to the surface to be within the reach of the motor foot). This suggests that the most efficient means of reducing turtle fatalities due to boat collisions would be to reduce the speeds of vessels to below planing speed and promote the use of jet-drive type propulsion systems.

The tests described here were conducted in calm water conditions, and did not include significant movement of the sea turtle models prior to collision. It is possible that waves or diving behavior of turtles could result in slightly different results for situations with boat speeds and configurations matching those in the tests described here. But the tests clearly indicate that:

1) Reducing the vessel speed bellowing planing reduces the possibility of fatal injuries in sea turtles. With the conventional outboard, this was true regardless of whether a propeller guard was installed or not: 25% of all idle speed tests resulted in catastrophic damage, compared to 100% at planing speed.
2) A speed that is just below planing speed reduced the likelihood of impact to the animal, compared to planing speed tests. It appeared that the resulting large bow wave helped push the animal out of the way, resulting in no contact with the animal in 38% of the sub-planing speed tests.
3) The Hydroshield® and Prop Buddy® did not significantly reduce the risk of catastrophic damage to the sea turtle models (10% catastrophic damage at idle speed with propeller guards vs. 40% with standard motor configuration at idle speed, 100% catastrophic damage at planing speed with all configurations).
4) Both of the jet propulsion systems significantly reduced damage to the model animals (no damage classified as catastrophic), compared to similar tests with the conventional motor configuration.
5) A highly buoyant sea turtle model sustained similar blunt force injuries observed during standard surface tests. This suggests that blunt force injuries

my occur post-mortem, but observed damage is not a reliable indicator of whether death occurred prior to or as a result of a collision.

Unfortunately the jet propulsion system deployed on a nearly flat-bottomed boat results in degradation of boat handling to some degree, and the jet outboard is less efficient hydraulically than a conventional propeller. It is also worth noting that there are several other parameters or issues that have not been investigated, such as the influence of hull shape, waves, attitude of the animal in the water, or other common propulsion configurations such as a fixed-axis propeller and rudder or twin outboards. However, the results are also somewhat encouraging in demonstrating that both boat equipment and the way it is operated can be modified to reduce the likelihood of fatal interactions between small boats and turtles. The same changes that would make waterways safer for turtles would also be expected to reduce risks to manatees, whales, and humans in the water.

APPENDIX A

TENSILE TESTS OF MODEL CARAPACE

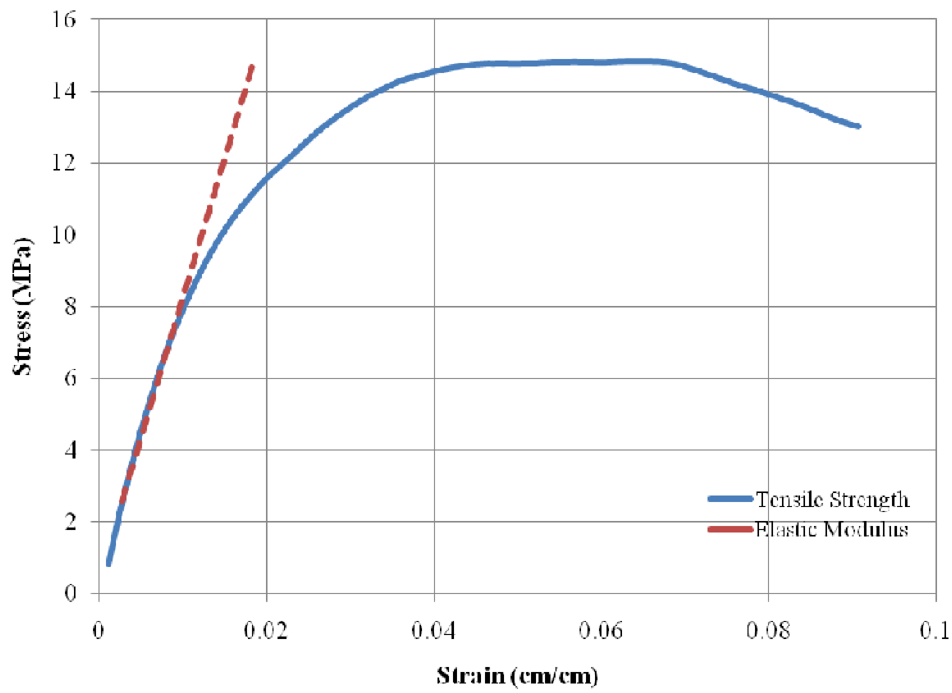


Figure A1. Tensile stress strain curve for test sample number 1 for the double layer with Coremat® spacer.

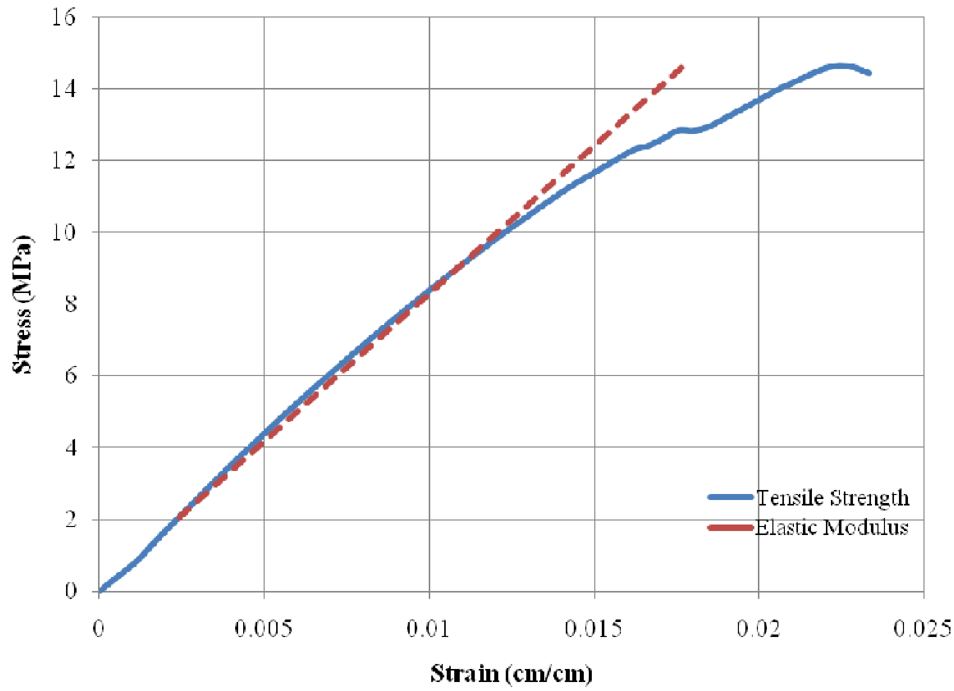


Figure A2. Tensile stress strain curve for test sample number 2 for the double layer with Coremat® spacer.

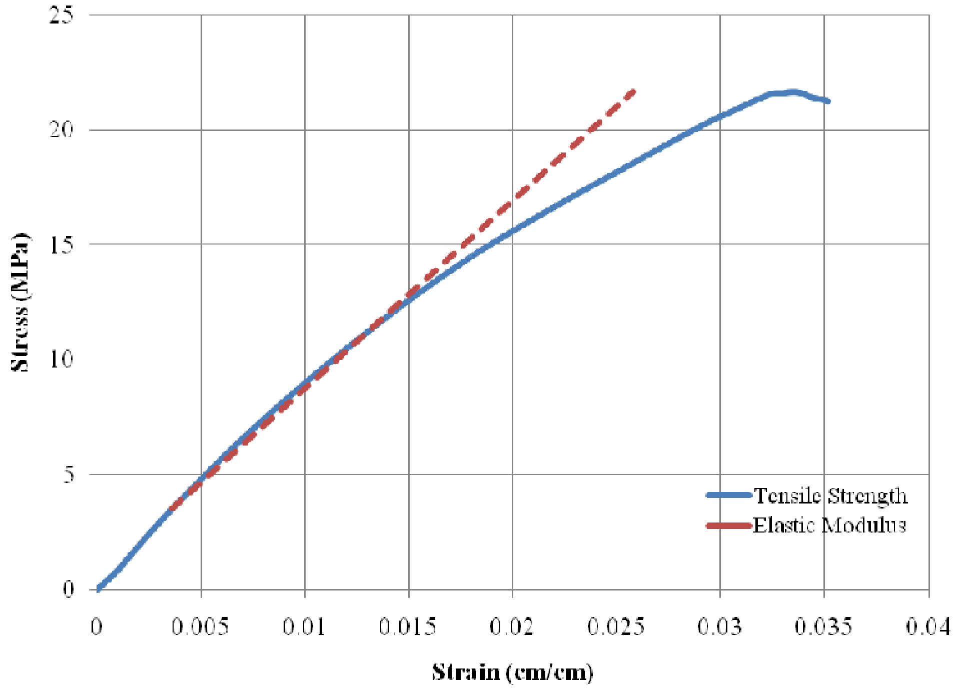


Figure A3. Tensile stress strain curve for test sample number 3 for the double layer with Coremat® spacer.

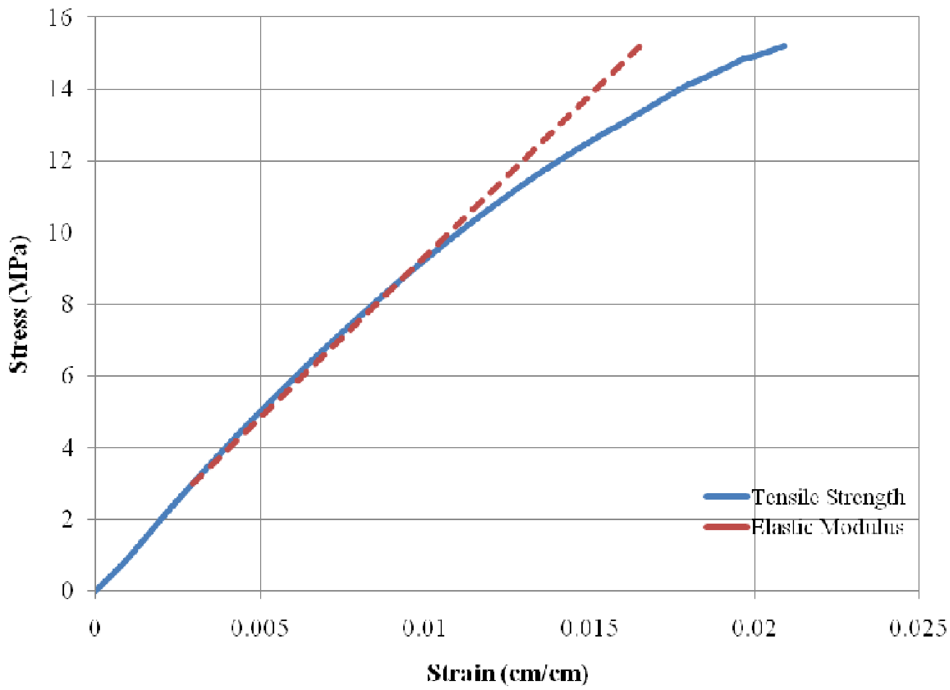


Figure A4. Tensile stress strain curve for test sample number 6 for the double layer with Coremat® spacer.

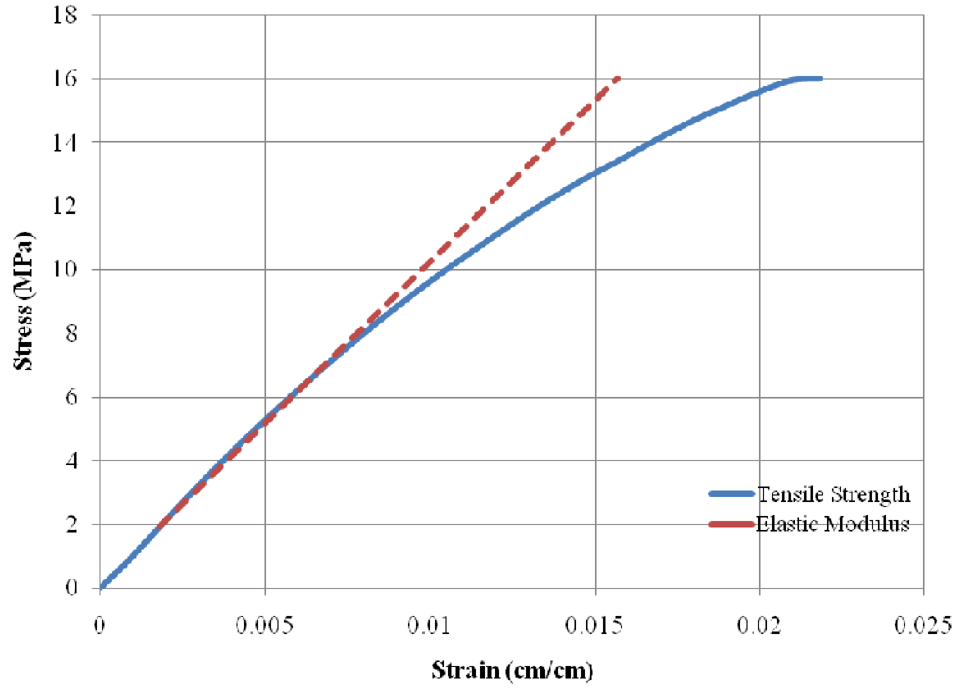


Figure A5. Tensile stress strain curve for test sample number 7 for the double layer with Coremat® spacer.

APPENDIX B

SAMPLE DATA COLLECTION SHEET FOR FIELD TESTS

Data Collection Sheet

Date: ____________________ Time: _________________ Initials: ____________

Test (Shell) Number: ___________________ Frame Number: ___________________

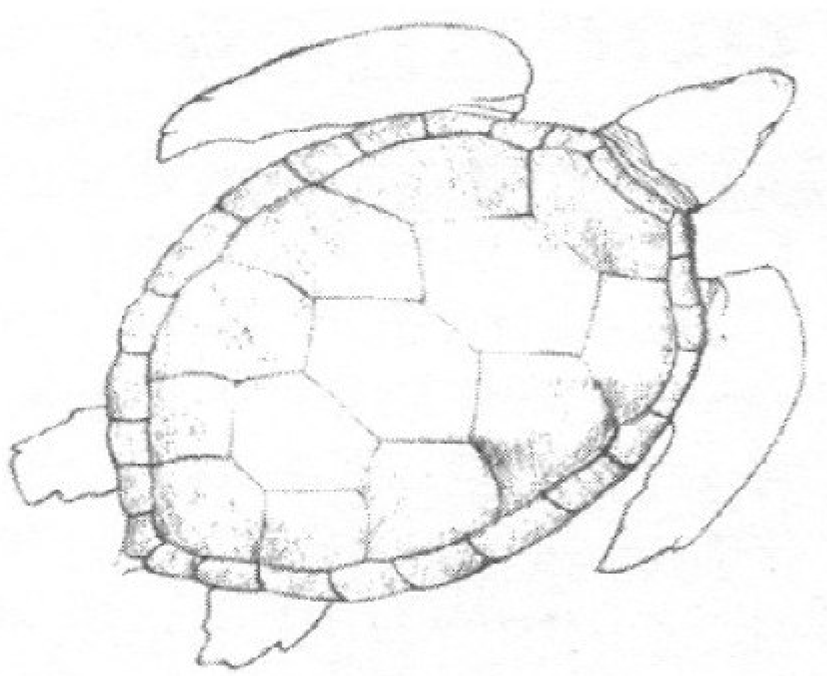
Accelerometer Number: ________________ Test Code: _________________________

Configuration Codes	Speed Codes	Depth Codes	Trial Number
N = Normal Config	I = Idle Speed	A = Surface	Number sequentally for each set of tests
B = Prop-Buddy	S = Subplaning Speed	Z = Prop	
H = HydroShield	P = Planing Speed		
S = Jet Ski		Example: Trial number 3 with the Prop-Buddy at idle speed,	
J = Jet Drive		at surface would be coded BIA3	

Type of wound (Blunt trauma, prop cut): ____

Size/Location of cuts/damage:

Sketch of damage:



Comments:

Appendix C

Table of Results

Table C1. Results table for every test performed including comments recorded in the field on the data sheets. “Standard” propulsion system means conventional outboard motor with propeller and no guard. Hydroshield® and Prop Buddy® are two types of guards attached to standard outboard motor. Idle speed is defined at 7 km/hr, sub-planing is 14 km/hr, and planing is 40 km/hr. Prop depth means depth to center of propeller when at rest. “NA” indicates that type of injury is not applicable to that trial. “Standard” motor means outboard with conventional propeller and no propeller guard. Wounds that were judged to be catastrophic are indicated with an “X.” Boat orientation defined in Figure 4.3.

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
1	Surface	Idle	Standard	6.5	2-1	No visible damage.	NA	NA	
2	Surface	Idle	Standard	7	4	2 small prop marks, rear.	10.6	NA	X
3	Surface	Idle	Standard	6.5	3-4	Small notch in 3-4 position.	5.1	NA	
4	Surface	Idle	Standard	6.6	3	Minor scrape on top of carapace.	NA	NA	
5	Surface	Idle	Standard	7	3-4	Prop cuts in the 3-4 position.	11.7	NA	X
6	Prop	Idle	Standard	6.5	2	Small notch in 3-4 position.	1.8	NA	
7	Prop	Idle	Standard	6.2	4	No contact.	NA	NA	
7	Prop	Idle	Standard	6.3	3	No visible damage	NA	NA	
8	Prop	Idle	Standard	6.4	4-1	No visible damage	NA	NA	
9	Prop	Idle	Standard	7.2	3-4	No visible damage	NA	NA	

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
10	Prop	Idle	Standard	6.6	1-2	Prop cuts in the 2-3 to 2 position.	15.2	NA	X
11	Prop	Sub-planing	Standard	15.5	3-4	No visible damage to carapace, frame smashed	NA	NA	
12	Prop	Sub-planing	Standard	17.9	1-4	Small prop cuts in carapace at 2-3 position. Prop marks on the frame.	8.4	NA	
13	Prop	Sub-planing	Standard	14.9	4	Large prop cuts from position 3 to 4. Piece of carapace cut off at position 4.	53.3	0.83%	X
14	Prop	Sub-planing	Standard	14	3	Small cut at position 1-2.	NA	< 0.2%	
15	Prop	Sub-planing	Standard	15.2	3	Very small cut at position 1-4. Frame busted at shoulder.	NA	< 0.2 %	
16	Surface	Sub-planing	Standard	15.4	2	Prop cuts along the edge of carapace at position 2.	27.4	NA	X
17	Surface	Sub-planing	Standard	14.3	4	Prop cuts along the edge of carapace at position 3-4.	50	NA	X
18	Surface	Sub-planing	Standard	13.9	1-4	No visible damage	NA	NA	
19	Surface	Sub-planing	Standard	15.4	2-3	No boat contact	NA	NA	
19	Surface	Sub-planing	Standard			No visible damage.	NA	NA	
20	Surface	Sub-planing	Standard	16.3	2-3	No contact	NA	NA	

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
20	Surface	Sub-planing	Standard	16.2	1-2	No contact	NA	NA	
20	Surface	Sub-planing	Standard	15.9	1	No contact	NA	NA	
20	Surface	Sub-planing	Standard	15.4	1	No contact	NA	NA	
20	Surface	Sub-planing	Standard	15.5	2	No contact	NA	NA	
20	Surface	Sub-planing	Standard	14	4	Five tests, no contact between boat and animal.	NA	NA	
22	Prop	Planing	Standard	44.2	2-3	Skeg mark and prop cuts across top of carapace from 2-3 to 1-4.	79.8	0.25%	X
23	Prop	Planing	Standard	40.1	3	Blunt impact at position 3. Possible prop cut at position 2-3.	12	5.50%	X
24	Prop	Planing	Standard	41.5	3-4	Skeg mark and prop cuts from position 1-4.	40.1	NA	X
25	Prop	Planing	Standard	42.7	3-4	Prop cuts and major damage along the left side from position 3-4 to 1.	101	8.30%	X
26	Prop	Planing	Standard	42	3-4	Skeg, prop cut across top of carapace from position 4 to position 1-2.	35.6	1.50%	X
21	Surface	Planing	Standard	41.7	1	Blunt force and/or prop damage, some tearing at position 1-4.	NA	32.60%	X
27	Surface	Planing	Standard	40.1	1-2	Blunt force/ prop damage at position 2. A lot of frame damage.	NA	5.60%	X

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
28	Surface	Planing	Standard	41.6	1-4	Ragged cut along the edge at position 3-4.	NA	3.60%	X
29	Surface	Planing	Standard	42.7	1	Blunt force/ prop damage at position 2. A lot of frame damage.	40.6	5.70%	X
30	Surface	Planing	Standard	41.6	3	Blunt force damage at position 2-3. Major frame damage.	NA	4.30%	X
31	Prop	Idle	Hydroshield®	6.5	2	Mark with very slight tear at position 2.	NA	NA	
31	Prop	Idle	Hydroshield®	6.3	3	Mark with very slight tear at position 3.	NA	NA	
31	Prop	Idle	Hydroshield®	6.3	1	Mark with no tear at position 1.	NA	NA	
31	Prop	Idle	Hydroshield®	6.4	2	Prop cuts on edge at position 2-3.	20	NA	X
32	Prop	Idle	Hydroshield®	7	2	Mark with very minor damage at position 2.	NA	NA	
32	Prop	Planing	Hydroshield®	41.2	1	Blunt wound with prop cuts at position 1-2. Major frame damage.	150	9.70%	X
33	Prop	Planing	Hydroshield®	40.7	3-4	Prop cuts from position 1-4 to 1-2.	73.7	NA	X
34	Prop	Planing	Hydroshield®	40.7	1-4	Blunt puncture, top of carapace, left side.	NA	0.30%	X
35	Prop	Planing	Hydroshield®	39.8	2-3	Blunt puncture, mark from position 2-3 to 4-1. Hole in top of carapace, middle.	NA	0.20%	X

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
36	Prop	Planing	Hydroshield®	38.7	1-4	Blunt skeg tear out, major damage at position 1-4.	NA	27.93%	X
37	Prop	Idle	Prop Buddy®	5.8	1-2	No visible damage	NA	NA	
37	Prop	Idle	Prop Buddy®	5.9	4	No visible damage	NA	NA	
37	Prop	Idle	Prop Buddy®	6.3	1-4	No visible damage	NA	NA	
37	Prop	Idle	Prop Buddy®	6.4	1	No visible damage	NA	NA	
37	Prop	Idle	Prop Buddy®	6.2	1	No visible damage	NA	NA	
37	Prop	Planing	Prop Buddy®	39.7	4	Blunt strike, large tear out at position 3-4.	NA	11%	X
38	Prop	Planing	Prop Buddy®	41	1	Blunt strike, large tear out at position 1-4.	NA	9.30%	X
39	Prop	Planing	Prop Buddy®	42	1-2?	Blunt strike, large tear out at position 1-2.	NA	11.10%	X
40	Prop	Planing	Prop Buddy®	40	1?	Blunt strike, large tear out at position 2.	NA	4.90%	X
51	Prop	Idle	Jet Outboard	6.5	3	Contact, no damage. Animal was not positioned low enough in water.	NA	NA	
51	Prop	Idle	Jet Outboard	6.5	1-2	No contact.	NA	NA	

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
51	Prop	Idle	Jet Outboard	7.1	1-2	No contact.	NA	NA	
51	Prop	Idle	Jet Outboard	7.2	2	No contact.	NA	NA	
51	Prop	Idle	Jet Outboard	6.9	1-2	No contact.	NA	NA	
51	Prop	Idle	Jet Outboard	7.1	1	No contact.	NA	NA	
51	Prop	Planing	Jet Outboard	40.6	2-3	No contact.	NA	NA	
51	Prop	Planing	Jet Outboard	42.3	1	No contact.	NA	NA	
51	Prop	Planing	Jet Outboard	45.3	1	No contact.	NA	NA	
51	Prop	Planing	Jet Outboard	39.2	1-4	No contact.	NA	NA	
51	Prop	Planing	Jet Outboard	42.3	3-4	No contact.	NA	NA	
51	Prop	Idle	Jet Ski	6.44	2-3	No contact.	NA	NA	
51	Prop	Idle	Jet Ski	6.44	2	No contact.	NA	NA	
51	Prop	Idle	Jet Ski	6.44	2	No contact.	NA	NA	

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
51	Prop	Idle	Jet Ski	6.44	3	No contact.	NA	NA	
51	Prop	Idle	Jet Ski	6.44	3	No contact.	NA	NA	
51	Prop	Planing	Jet Ski	41.86	1	No contact.	NA	NA	
51	Prop	Planing	Jet Ski	43.47	4	No contact.	NA	NA	
51	Prop	Planing	Jet Ski	41.86	4	No contact.	NA	NA	
51	Prop	Planing	Jet Ski	40.25	3	No contact.	NA	NA	
51	Prop	Planing	Jet Ski	41.86	3	No contact.	NA	NA	
51	Surface	Idle	Jet Ski	6.44	3	No visible damage.	NA	NA	
51	Surface	Idle	Jet Ski	6.44	2	No visible damage.	NA	NA	
51	Surface	Idle	Jet Ski	6.44	3	No visible damage.	NA	NA	
51	Surface	Idle	Jet Ski	6.44	2-3	No visible damage.	NA	NA	
51	Surface	Idle	Jet Ski	6.44	1-2	No visible damage.	NA	NA	

Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
51	Surface	Idle	Jet Outboard	7.1	1	No motor impact, boat impact. No damage.	NA	NA	
51	Surface	Idle	Jet Outboard	6.5	3	No visible damage.	NA	NA	
51	Surface	Idle	Jet Outboard	6.6	1-2	No visible damage.	NA	NA	
51	Surface	Idle	Jet Outboard	6.3	1	No visible damage.	NA	NA	
51	Surface	Idle	Jet Outboard	5.9	3	No visible damage.	NA	NA	
51	Surface	Planing	Jet Outboard	42.6	1	Small cut, not through the carapace. 2 lines from intake grating on top of carapace.	NA	NA	
52	Surface	Planing	Jet Outboard	44.1	4	Small scrapes, 4 grating marks on top of carapace.	NA	NA	
53	Surface	Planing	Jet Outboard	41	2	10 intake grating marks on top of carapace.	NA	NA	
54	Surface	Planing	Jet Outboard	43.1	1-4	6 intake grating marks and a small slice on top of the carapace.	NA	NA	
55	Surface	Planing	Jet Outboard	38.7	1-4	3 grate marks, no slices or cuts.	NA	NA	
56	Surface	Planing	Jet Ski	41.86	1	Light scraping area on top of carapace.	NA	NA	
57	Surface	Planing	Jet Ski	43.47	2	Light scrapes on top of carapace.	NA	NA	

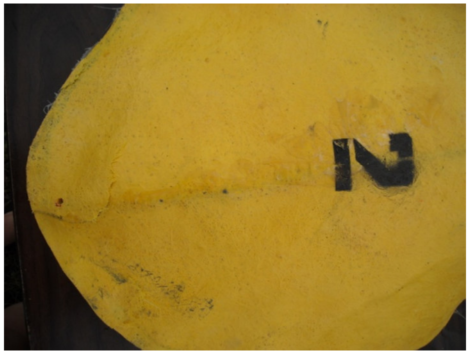
Carapace Number	Animal Position	Boat Speed	Motor Configuration	Speed (km/h)	Initial Boat Orientation	Comments from Data Sheets	Total length of cuts (cm)	Percent of Total Area Damaged	Catastrophic
58	Surface	Planing	Jet Ski	40.25	2	Light scrapes on surface, no cuts.	NA	NA	
59	Surface	Planing	Jet Ski	43.47	2-3	Glancing blow at impact. Two light scrape marks, no cuts.	NA	NA	
60	Surface	Planing	Jet Ski	43.47	1-2	Light scrapes, no cuts or gouges.	NA	NA	
1	Floater	Planing	Standard	40	3	Severe damage. Skeg and prop cuts at position 3. 9 kg weight on frame.	10.2	14.70%	X
3	Floater	Planing	Standard	43.2	1-2	4 prop cuts at position 2-3.	NA	4.10%	X
4	Floater	Planing	Standard	38.5	3	Major blunt impact at position 3-4.	26.7	4.80%	X
5	Floater	Planing	Standard	39.2	2	Little or no carapace damage, major frame damage.	NA	NA	
6	Floater	Planing	Standard	42.5	4	Major frame and carapace damage, blunt impact at position 3-4.	NA	15.40%	X

Appendix D

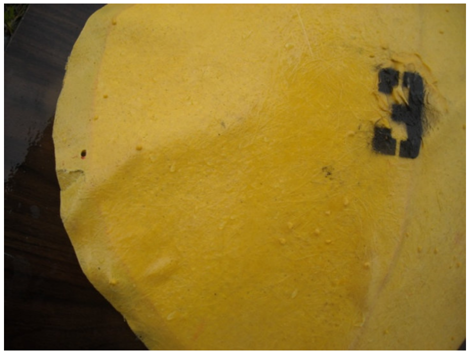
Post-Test Photographs of Each Carapace

Figure D.1. Photos of model carapaces tested with standard motor configuration, animal at surface, idle speed. Comments of damage included below each photograph.

No visible damage.



Small prop marks at position 2-3.



Small notch at position 4.

Minor scrape on top on top of shell.

Prop cuts in the 3-4 position.

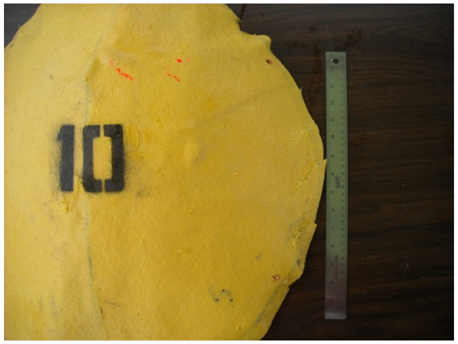
Figure D.2. Photographs of model carapaces tested with Standard motor configuration, animal at prop depth, idle speed. Comments of damage included under each photograph.

Small notch in the 3-4 position.

No visible damage.

No visible damage.

No visible damage.



Prop cuts at position 2.

Underside of cuts on shell number 10.

Figure D.3. Photographs of model carapaces tested with standard motor configuration, animal at prop depth, sub-planing speed. Comments of damage included below each photograph.

No visible damage to shell. Frame smashed, cut at position 1-2.

Small prop cuts on shell in 2-3 position. Slices through frame at position 2-3.

Large prop cuts at position 3-4. Piece of shell missing at position 4.

Small cut at position 1-2.

Small cut at position 1-4.

Damage to the frame from test on shell number 11.

Figure D.4. Photographs of model carapaces tested with standard motor configuration, animal at surface, sub-planing speed. Comments of damage included below each photograph.

Prop cuts along the edge at position 2.

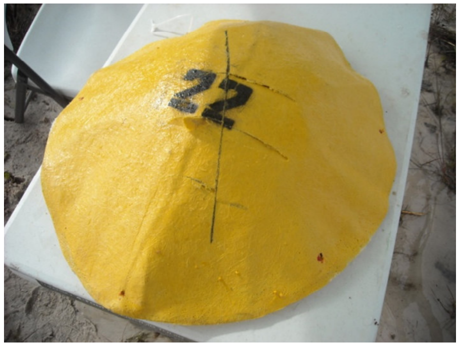
Prop cuts along the edge at position 3-4.

No visible damage.

No visible damage.

5 tests run, no contact with shell.

Figure D.5. Photographs of model carapaces tested with standard motor configuration, animal at surface, planing speed. Comments of damage included below each photograph.



Skeg mark and prop cuts across the top of the shell from position 2-3 to 1-4.

Blunt force wound at position 3, possible prop cut at position 2-3.

Skeg mark and prop cuts from position 1 to position 4.

Prop cuts and major damage along left side from position 3 to position 1.

Skeg mark and prop cuts across top of shell from position 4 to position 1-2.

All of the shells from this test group.

Figure D.6. Photographs of model carapaces tested with standard motor configuration, animal at surface, planing speed. Comments of damage included below each photograph.

Blunt force and/or prop wound at position 1-4.

Blunt force at position 1-2. Severe frame damage.

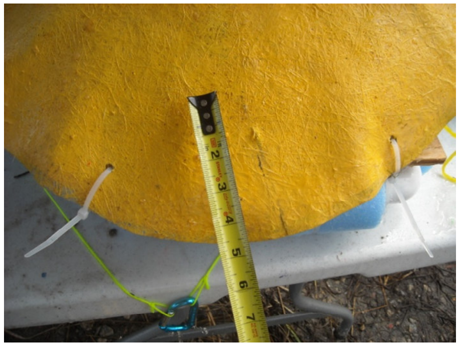
Ragged cut along the edge at position 3-4.

Blunt force and/or prop wound at position 2. Severe frame damage.

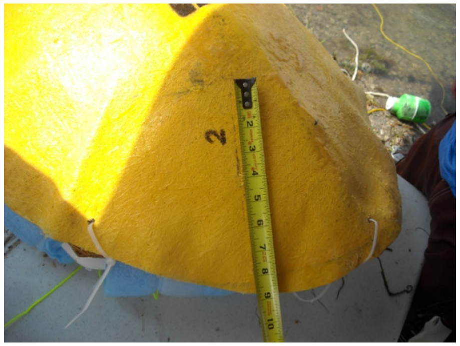
Blunt force at position 2-3. Major frame damage.

All the shells from this test group.

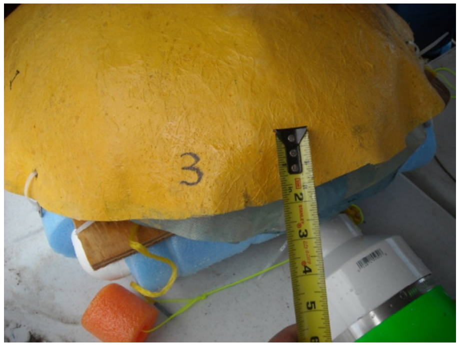
Figure D.7. Photographs of model carapaces tested with outboard motor with Hydroshield®, animal at prop depth, idle speed. Comments of damage included below each photograph.



Mark with very slight tear at position 2.



Mark with very slight tear at position 3.



Mark with not tear at position 1.

Prop cuts on edge at position 2-3.

Mark with very minor damage on edge at position 2.

Figure D.8. Photographs of model carapaces tested with outboard motor with Hydroshield®, animal at prop depth, planing speed. Comments of damage included below each photograph.

Blunt wound with prop cuts at position 1-2. Major frame damage.

Prop cuts along top of shell from position 1-4 to 1-2.

Blunt puncture, top of shell, left side.

Blunt puncture top of shell, middle. Mark across shell from 2-3 to 4-1.

Blunt/ skeg tear off damage at position 1-4.

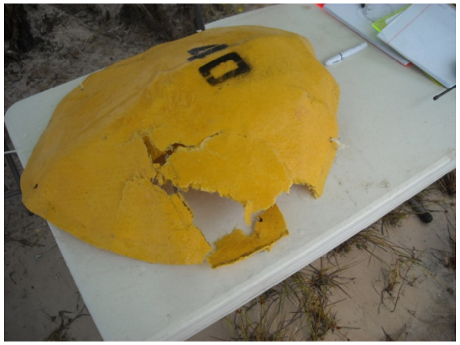
All of the shells from this test group.

Figure D.9. Photographs of model carapaces tested with outboard motor with Prop Buddy, animal at prop depth, planing speed. Comments of damage included below each photograph.

Blunt strike, large tear out at position 4.

Blunt strike, large tear out at position 1-4.

Blunt strike, large tear out at position 1-2.



Blunt strike, large tear out at position 2.

All shells from this group.

Figure D.10. Photographs of model carapaces tested with jet drive motor, animal at surface, planing speed. Comments of damage included below each photograph.

Small cut, not through. 2 lines from intake grating on top.

Small scrapes, 4 grating marks on top.

10 intake grating marks on top.

6 intake grating marks on top, small scrape.

3 grate marks, no slices or cuts.

All of the shells from this test group.

Figure D.11. Photographs of model carapaces tested with Jet Ski, animal at surface, planing speed. Comments of damage included below each photograph.

Light scraping on top of the shell.

Light scrapes on top of the shell.

Light scrapes on surface, no cuts.

Glancing blow at impact, 2 light scrapes, no cuts.

Light scrapes, no cuts or gouges.

All of the shells from this test group.

Figure D.12. Photographs of model carapaces tested with standard motor configuration, “floater” animal, planing speed. Comments of damage included below each photograph.

Severe damage. Skeg and prop cuts at position 3.

4 prop cuts penetrate shell at position 2.

Major blunt impact at position 3-4.

No visible shell damage. Major frame damage.

Major frame and shell damage. Blunt impact at position 3-4.

All of the shells from this test group.

REFERENCES

An, Y.H. and Draughn, R.A., (2000), Mechanical Testing of Bone and Bone-Implant Interface, RCR Press, Boca Raton, FL, pp. 175-206.

Burstein, A.H., Reilly, D.T., and Martins, M. (1976), Aging of bone tissue: Mechanical properties. *Journal of Bone and Joint Surgery Am.*, Vol. 58, pp 82-86.

Clifton, K.B., Yan, J., Mecholsky, J.J., and Reep, R.L. (2007), Material properties of manatee rib bone. *Journal of Zoology*, Vol. 274, pp. 150-159.

Curran, A.P., and Morris, J.G. (1988), The effect of boat traffic on manatee (*Trichechus manatus*) densities at selected sites on the Indian and Banana River Lagoons, Brevard County Florida. *American Society of Zoologists.* Meeting Abstract.

Currey, J.D. (1984), Effects of differences in mineralization on the mechanical properties of bone. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, Vol. 304, No. 1121, pp. 509-518.

Cytel Statistical Software Inc. 675 Massachusetts Ave., Cambridge, MA 02139.

Dodd, C.K. (2006). A bibliography of the loggerhead sea turtle *Caretta caretta* (Linnaeus, 1758) including references to fossils placed in the genus *Caretta*. <www.flmnh.ufl.edu/natsci/herpetology/caretta/caretta.htm>.

Douglas, A.B., Calambokidis, J., Raverty, S., Jeffries, S.J., Lambourn, D.M., and Norman, S.A. (2008), Incidence of ship strikes of large whales in Washington State. *Journal of the Marine Biological Association of the United Kingdom*, Vol. 88, No. 6, pp. 1121-1132.

Ernst, C., Lovich, J., and Barbour, R. (1994). Turtles of the United States and Canada. *Smithsonian Institution Press*, Washington, D.C.

Garita, B. and Rapoff, A. J. (2003). Biomimetic design from bone. *Experimental Techniques, Biomechanics Series*, Part 4, pp. 36-39.

George, J.C., Philo, L.M., Hazard, K., Withrow, D., Carroll, G.M., and Suydam, R. (1994), Frequency of killer-whale (*Orcinus-orca*) attacks and ship collisions based on scarring on bowhead whales (*Balaena-mysticetus*) of the Bering-Chukchi-Beaufort Sea stock. *Arctic*, Vol. 47, No. 3, pp. 247-255.

Gilman, E., Kobayashi, D., Swenarton, T., Brothers, N., Dalzell, P., Kinan-Kelly, I. (2008). Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. *Biological Conservation*, Vol. 139, pp. 19 – 28.

Hart, K., Mooreside, P., Crowder, L. (2006). Interpreting the spatio-temporal patterns of sea turtle strandings: Going with the flow. *Biological Conservation*, Vol. 129, pp. 283-290.

Hazel, J. (2006). Vessel-related mortality of sea turtles in Queensland, Australia. *Wildlife Research*, Vol. 33, pp. 149 – 154.

Hazel, J., Lawler, I.R., Marsh, H., Robson, S. (2007). Vessel speed increases collision risk for the green turtle *Chelonia mydas*. *Endangered Species Research*, Vol. 3, No. 2, pp. 105 – 113.

Hazel, J., Lawler, I., Hamann, M. (2009). Diving at the shallow end: Green turtle behavior in near-shore foraging habitat. *Journal of Experimental Marine Biology and Ecology*, Vol. 371, pp. 84 – 92.

Hochscheid, S., Betivegna, F., Speakman, J. (2003). The dual function of the lung in chelonian sea turtles: buoyancy control and oxygen storage. *Journal of Experimental Marine Biology and Ecology*, Vol. 279, pp. 123 – 140.

Hodges, J. (2008). Evaluation of turtle shell properties and prototype biomimetic shell fabrication. M.S. thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology, Savannah Campus.

IUCN (2006). *2006 IUNC Red List of Threatened Species*. <www.iucnredlist.org>

Karchin, A. (2004). Mechanical properties of biomaterials. University of Washington Engineered Biomaterials. <www.uweb.engr.washington.edu/research/tutorials/mechproperties.html>

Kirkman, T.W. (1996), Statistics to Use. <http://www.physics.csbsju.edu/stats/> Accessed (15 March, 2010)

Li, S. H., Zeng, Q. L., Xiao, L., Fu, S. Y., and Zhou, B. L. (1995), Biomimicry of bamboo bast fiber with engineering composite materials. *Materials Science and Engineering*, Vol. 3, pp. 125-130.

Magnuson, J.J., Bjorndal, K.A., DuPaul, W.D., Graham, G.L., Owens, D.W., Peterson, C.H., Pritchard, P.C.H., Richardson, J.I., Saul, G.E. and West, C.W. (1990). Decline of the Sea Turtles: Causes and Prevention. National Research Council, National Academy of Sciences, Washington, D.C., pp 259.

Marmontel, M., Humphrey, S.R., O'Shea, T.J. (1997), Population viability analysis of the Florida manatee (*Trichechus manatus latirostris*), 1976-1991. *Conservations Biology*, Vol. 11, No. 2, pp. 467-481.

Mayer, G. (2005), Rigid biological systems as models for synthetic composites. *Science Magazine*, Vol. 310, No. 5751, pp. 1144-1147.

Milthorpe, B.K., Rogers, G.J., and Schindhelm, K. (1987), Microcomputer – based system for tensile testing of biological materials. *Medical and Biological Engineering and Computing*, Vol. 26, No.2, pp. 161-166.

National Marine Fisheries Service and the U. S. Fish and Wildlife Service (1991). Recovery plan for the Northwest Atlantic. population of loggerhead sea turtle *Caretta caretta,* .second revision. National Fisheries Service, Washington, D.C.

National Marine Fisheries Service and the U. S. Fish and Wildlife Service (2007). Loggerhead Sea Turtle (*Caretta caretta*) 5-Year Review: Summary and Evaluation. National Fisheries Service, Washington, D.C.

Orós, J., Torrent, A., Calabuig, P., Déniz, S. (2005). Diseases and causes of mortality among sea turtles stranded in the Canary Islands, Spain (1998-2002). *Diseases of Aquatic Organisms*, Vol. 63, pp. 13-24.

Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A., and Weinrich, M.T. (2006). Mediterranean fin whales at risk from fatal ship strikes. *Marine Pollution Bulletin*, Vol. 52, No. 10, pp. 1287-1298.

Plotkin, P.T. (Editor) (1995). National Marine Fisheries Service and U.S. Fish and Wildlife Service Status Reviews for Sea Turtles Listed under the Endangered Species Act of 1973. National Marine Fisheries Service, Silver Springs, Maryland.

Thomas, J., Gozalbes, P., Raga, J.A., Godley, B. (2008). Bycatch of loggerhead sea turtles: insights from 14 years of stranding data. *Endangered Species Research*, Vol. 5, pp. 161 – 169.

U.S. Fish and Wildlife Service (1978). Listing and Protecting Loggerhead Sea Turtles as 'Threatened Species' and Populations of Green and Olive Ridley Sea Turtles and Threatened Species or 'Endangered Species'. Federal Register, Vol. 43, No. 146.

Venizelos, L.E. (1993). Speed boats kill turtles in Laganas Bay, Zakynthos. *Marine Turtle News*, Vol. 63, pp. 15.

Zydelis, R., Wallace, B., Gilman, E., Werner, T. (2003). Conservation of marine megafauna through minimization of fisheries bycatch. *Conservation Biology*, Vol. 23, No. 3, pp. 608 – 616.